

ESTIMATES OF ABUNDANCE OF NORTHEASTERN OFFSHORE SPOTTED,  
COASTAL SPOTTED, AND EASTERN SPINNER DOLPHINS  
IN THE EASTERN TROPICAL PACIFIC OCEAN

Tim Gerrodette

Jaume Forcada

Southwest Fisheries Science Center

La Jolla, California

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## ABSTRACT

Stratified large-scale line-transect surveys were carried out with oceanographic research vessels in the eastern tropical Pacific Ocean in 12 different years between 1979 and 2000. The surveys were designed to estimate the abundance of northeastern offshore spotted (*Stenella attenuata*) and eastern spinner (*S. longirostris orientalis*) dolphins, which are affected by the purse-seine tuna fishery for yellowfin tuna (*Thunnus albacares*). In the most recent surveys in 1998-2000, estimates of the coastal subspecies of spotted dolphins (*S. attenuata graffmani*) were also possible. Searching was carried out primarily with pedestal-mounted 25x150 binoculars fitted with azimuth rings and reticles for angle and distance measurements. Aerial photography was used to measure dolphin school sizes when possible, and to improve observers' estimates of school size when not. Estimates of dolphin abundance for each stock were based on modified line-transect methods, using covariates to model the detection process and group size. Variances and confidence intervals were estimated by bootstrap. For the 21-year period, the low and high total estimates of abundance (in numbers of animals) were: 494,268 to 953,547 for northeastern offshore spotted dolphins, 271,322 to 741,867 for eastern spinner dolphins, and 96,738 to 228,038 for coastal spotted dolphins. Weighted linear and quadratic regressions of abundance against time were not statistically significant for either northeastern offshore spotted or eastern spinner dolphins.

## INTRODUCTION

The purse-seine fishery for yellowfin tuna (*Thunnus albacares*) in the eastern tropical Pacific Ocean (ETP) utilizes the association of seabirds, dolphins and fish to locate and catch schools of large tuna (Perrin 1969, Au and Pitman 1986, National Research Council 1992, Gerrodette 2002). However, the large bycatch of dolphins in the early years of the fishery led to the decline of several species of dolphins (Smith 1983, Wade 1993b). Between 1986 and 1993 the number of dolphins reported killed by observers on fishing vessels declined by more than 95%, and the current reported mortality is at a low level relative to estimates of population size (Hall and Lennert 1997), leading to expectations that the dolphin populations should be recovering.

Range-wide surveys to estimate abundance of the affected dolphin species were last undertaken annually from 1986-1990 (Wade and Gerrodette 1993). Indices of relative abundance derived from dolphin sightings on fishing vessels indicate declining (or at least non-increasing) abundance over the last decade (Lennert-Cody et al. 2001). However, these indices have biases that have changed with time, making their reliability to measure recovery (or lack thereof) questionable (Lennert-Cody et al. 2001). In 1997, the U.S. Congress passed the International Dolphin Conservation Program Act (Public Law 105-42) as part of an international agreement to address the dolphin bycatch problem (AIDCP 1998, Gosliner 1999). This legislation directed the National Marine Fisheries Service to determine if the chase and encirclement of dolphins in the fishery was having a significant adverse impact on depleted dolphin stocks. As part of this determination, Congress specified that research cruises be undertaken in 1998, 1999 and 2000 to generate new estimates of dolphin abundance.

Abundance estimates based on the 1986-1990 cruises have previously been published as annual estimates for dolphins (Wade and Gerrodette 1992), and as pooled estimates over the entire 5-year period for all cetacean species (Wade and Gerrodette 1993). Preliminary estimates of abundance for 1998 and 1999 have also been produced for the dolphin populations most affected by the fishery (Gerrodette 1999, 2000). All of these previous estimates have been carried out with conventional line-transect methods (Buckland et al. 1993).

Recent advances in line-transect analysis permit modeling the probability of detecting cetaceans on a survey as a function of factors other than perpendicular distance alone (Marques 2001, Forcada 2002). Simulations have shown these new estimators to be more accurate and precise than traditional univariate methods (Forcada 2002). In addition, improved estimates of group size (Gerrodette et al. 2002) and distances from ship to sighting (Lerczak and Hobbs 1998, Kinzey and Gerrodette 2001, Kinzey et al. 2002) are now available. Here we use the new methods to estimate the abundance of ETP dolphin stocks depleted by the fishery, based on data collected in 1998-2000, together with a reanalysis of data from past cruises dating back to 1979. Estimates of dolphin abundance will be used to estimate the growth rates of the stocks (Wade 2002) as well as to set the annual limits on dolphin kill (AIDCP 1998).

## METHODS

### *Stocks and survey design*

The dolphin species with the highest number of dolphins killed in the fishery have been spotted dolphins and spinner dolphins (Smith 1983, Wade 1993a, b). Dolphin species in the ETP have been divided into stocks for management (Dizon et al. 1994). The stocks that have been designated as depleted under the Marine Mammal Protection Act, and which were therefore of primary interest in designing the survey, were the northeastern offshore spotted dolphin, *Stenella attenuata*, north of 5°N and east of 120°E (Perrin et al. 1994), and the eastern spinner dolphin, *Stenella longirostris orientalis* (Perrin 1990). The legal status of the coastal spotted dolphin, *Stenella attenuata graffmani* (Perrin et al. 1985), is somewhat uncertain, but since the stock may also be considered depleted, the survey was designed to produce an estimate of abundance for this stock as well. The range of the fishery and the affected dolphin populations is a large triangular area in the eastern tropical Pacific Ocean (Fig. 1). The outer boundaries of the survey area were drawn well beyond the limits of the target stocks, to be certain to include the entire populations (Gerrodette et al. 1998).

The surveys in 1998-2000 were carried out with multiple oceanographic research vessels each year. The NOAA Ships *David Starr Jordan* and *McArthur* were used in all three years, and the *Endeavor* from the University of Rhode Island was used in addition in 1998. All ships are similar in length (52-57m) and observer eye height (10.4-10.7m). In each year, the ships were in the study area for approximately four months, from late July through the first week in December, with port stops every 3-4 weeks. Details of itinerary, tracklines and personnel are given in the cruise data reports (Kinzey et al. 1999, 2000a, 2001).

Based on densities of animals and stocks of interest, searching effort was stratified into four areas: a core stratum centered on the main stocks of interest, north and south coastal strata

for stocks that occur only near the coast, and an outer stratum of lower density and effort (Fig. 2). The core stratum roughly corresponded to the ranges of the two dolphin stocks of main interest: northeastern offshore spotted and eastern spinner dolphins (Fig. 1). The outer boundary of the coastal strata was the 1000m depth contour. The allocation of effort between the core and outer stratum was based approximately on the relative sizes of the two strata and on the estimated eastern spinner dolphin density in the two strata from past studies (Buckland et al. 1993, Eqs. 7.7 and 7.11). In practice, the range of the research vessels required a port stop in the Hawaiian Islands, and this caused the outer stratum to be sampled at a higher intensity than past densities would strictly indicate. The intensity of search effort in the core stratum was about three times the effort in the outer stratum per unit area, and the effort in the coastal strata about twice the core. Within each stratum, transect lines were randomly placed to achieve uniform spatial coverage. Ships moved at night, which contributed to some independence among daily transects. The starting point of each day's transect effort was wherever the ship happened to be along the overall trackline.

### *Field methods*

Methods of collecting data followed standard protocols for line-transect surveys conducted by the SWFSC (Kinzey et al. 2000b, Barlow et al. 2001). In workable conditions, a visual search for cetaceans was conducted on the flying bridge of each vessel during all daylight hours as the ship moved along the trackline at a speed of 10 knots. On each ship, six marine mammal observers stood watch, three at a time. The team of three observers rotated positions every 40 minutes; thus, each observer stood watch for two hours, then had two hours rest. While on duty, two observers, one on each side of the ship, searched with pedestal-mounted 25x150 binoculars. Each 25X observer scanned from abeam (90E from the trackline) on the side of the vessel where the binocular was mounted to 10E past the trackline on the opposite side. Together, the two 25X observers thus searched the 180E forward of the ship with a 20E area of overlap near the trackline. The third observer searched by eye and with a hand-held 7X binocular, covering areas closer to the ship over the whole 180E.

When marine mammals were sighted, observers measured the distance to the animals. The 25X binoculars were fitted with azimuth rings on the pedestal for measurement of horizontal angles from the trackline to the animals, and reticles in the ocular lenses for measurement of vertical angles from the horizon to the animals in the water. Reticle values were converted to angular values (Kinzey and Gerrodette 2001), and angular values converted to distance from the observer, based on height above the water (Gordon 1990, Lerczak and Hobbs 1998). Distance measurements made with reticles were checked against radar measurements under a variety of field conditions and found to be accurate except for a slight tendency to underestimate beyond 4 km (Kinzey et al. 2002). Atmospheric refraction of light rays causes the horizon to be perceived slightly higher than it actually is, and hence distance to objects near the horizon to be underestimated (Leaper and Gordon 2001). Inclusion of a factor for refraction decreased this slight tendency to underestimate the distance to sightings near the horizon (Kinzey et al. 2002).

Data on sightings and transect effort were entered into a laptop computer by the observer who was currently not using a 25X binocular, using a customized data entry program. In addition to angle and reticle, Beaufort sea state, visibility, sun angle, swell height, presence of

birds and other factors that might affect detection probability were recorded with each sighting. The data entry program automatically recorded the position of the ship with a GPS signal from the ship. If the sighting was less than 5.6 km (3 nm) from the trackline, the team went "off-effort" and directed the ship to leave the trackline and to approach the animal(s) sighted. The observers identified the sighting to species or subspecies (if possible) and made group size estimates. Each observer team had at least one observer highly experienced in the field identification of marine mammals in the ETP. Observers discussed distinguishing field characteristics in order to obtain the best possible identification, but they estimated group sizes and, in the case of mixed-species schools, group composition, independently. When the cruise was completed, all data underwent a thorough checking and editing process (Jackson 2001).

### *School size*

For animals that occur in groups, accurate determination of the size of the group is fundamental for accurate estimation of abundance. Determining the size of a large groups of active cetaceans is a difficult task. Aerial photography was used to improve dolphin school size estimates. From 1987-2000, the *David Starr Jordan* carried a helicopter equipped with a medium-format, motion-compensated, military reconnaissance camera. In suitable conditions of sea state, sun angle and school configuration, it was possible to photograph entire schools of dolphins and to count the number of dolphins directly from the negatives (Gilpatrick 1993). However, aerial photographs were available for only a subset of schools seen on the *Jordan*, and none of the schools seen on the other ships. For most schools, school size was estimated from the best, high and low estimates made by each observer.

By comparing each observer's estimates of school size to the photographic counts, the observer's group size estimation tendencies could be assessed. Based on a regression of estimates on counts, individual correction or "calibration" factors for 52 observers were estimated (Gerrodette and Perrin 1991, Barlow et al. 1998, Gerrodette et al. 2002). These factors were used to produce a calibrated estimate of school size when the observer's original ("best") estimate of school size fell in the range of photographed schools for which he/she had been calibrated. Calibration factors were not available for every observer, either because (1) the observer worked prior to the start of the aerial calibration program in 1987, or (2) the observer had an insufficient number of photographed schools to estimate the regression coefficients. For school size estimates made by uncalibrated observers, or for schools which fell outside the range of school sizes for which an observer had been calibrated, we adjusted the observer's best estimate by dividing the estimate by 0.860, the mean of ratios of best estimate to photo count for the 52 calibrated observers (Gerrodette et al. 2002).

We combined the individual estimates made by each observer, adjusted as described above, to obtain a single estimate of school size for each school. Because the calibration procedure was based on the logarithm of the estimates, the weighting and averaging was also carried out on the logarithms, using the inverse of the variance of each observer as weights. The logarithm of the final calibrated estimate of school size for each sighting was

$$\ln \hat{s} = n^{-1} \sum_{i=1}^n w_i \ln C_i,$$

with variance

$$\text{var}(\ln \hat{s}) = n^{-1} \sum_{i=1}^n \frac{v_i w_i^2}{k_i},$$

where  $n$  = number of calibrated estimates  $C$  for the school,  $k_i$  = number of points (photographed schools) used to estimate the regression coefficients for the observer making the  $i$ -th estimate,  $w_i = v_i^{-1} / \sum v_i^{-1}$ , and  $v_i$  = residual variance from the regression of the log of school size estimates on log of photo counts for the observer making the  $i$ -th estimate (Gerrodette et al. 2002).

#### *Data and methods for previous surveys*

On previous cruises, the same basic data (positions at beginning and end of searching effort, angles and distances to sightings, and school sizes) were collected, although methods of collecting the data have evolved over the years. For example, previous data were recorded on paper rather than on laptop computer, and ship positions were measured with Loran or SatNav before the GPS system was available. On the earliest cruises (1979 and 1980), distance and angle from trackline were estimated by eye rather than with binocular reticles and angle rings. All surveys have been carried out by the same vessels, the *David Starr Jordan* and *McArthur*, except that the *Townsend Cromwell* joined the *Jordan* in 1979 and the *Endeavor* joined the *Jordan* and *McArthur* in 1998.

The surveys in 1986-90 were conducted at the same time of year as the 1998-2000 surveys, from late July to early December. In 1979, 1980 and 1983, the surveys were carried out in January-April, while the 1982 cruise took place in May-August. Time of year should not be an important factor affecting these estimates. Spotted and spinner dolphins are present in the area year-round, and the surveyed areas were large enough to include any small-scale seasonal movements of the dolphin populations (Reilly 1990).

The main differences for previous cruises was the amount and distribution of search effort. To analyze the data for the dolphin stocks of interest, different strata were used in different groups of years (Fig. 3). In 1979, effort was concentrated in a “calibration area” (Fig. 4, NES area 1 and ES area 1 in Figs. 3A and 3B). In 1980, 1982 and 1983, a single stratum for each stock was used (Fig. 3C); the amount of transect effort within these strata was modest in 1980 and 1982 and sparse in 1983 (Fig. 4). During 1986-1990, a more comprehensive series of cruises was undertaken (Holt et al. 1987). The four original strata of this series have been increased to six by subdividing the Inshore and Middle strata (Fig. 3D) to match the currently defined boundary of the northeastern stock of offshore spotted dolphins (Perrin et al. 1994). The Inshore and Middle strata received more trackline effort (Fig. 4) and produced most of the sightings on which estimates of abundance were based.

#### *Abundance estimation*

Estimation of abundance was based on distance sampling (Buckland et al. 2001). A multivariate extension of conventional line-transect analysis (Forcada 2002) estimated abundance  $N$  as

$$\hat{N} = \sum_j \frac{A_j}{2L_j} \sum_i \hat{f}_{ij}(0, c_{ij}) \hat{s}_{ij},$$

where  $A_j$  was the area and  $L_j$  the length of search effort in stratum  $j$ ,  $\hat{f}_{ij}(0, c_{ij})$  the estimated probability density evaluated at zero perpendicular distance of the  $i$ th sighting in stratum  $j$  under conditions  $c_{ij}$ , and  $\hat{s}_{ij}$  the estimated group size of the  $i$ th sighting in stratum  $j$  (subgroup size of the species of interest in the case of mixed-species schools). Estimation was based on search effort and sightings that occurred during on-effort periods, in conditions of Beaufort < 6 and visibility > 4km. It was conventionally assumed that all cetacean groups on or near the trackline were detected [*i.e.*,  $g(0)=1.0$ ]. This was likely to be true, at least to a close approximation, for all dolphins (see Discussion). The vector of covariates  $c_{ij}$  included continuous variables group size, Beaufort sea state and time of day, and categorical variables species, ship, stratum, sighting cue, glare, whether the school was a single- or mixed-species group, and whether seabirds were present or not. Sea state measured on the Beaufort scale was actually a discrete variable, but the ordinal scale could be modeled satisfactorily as a continuous variable (Barlow et al. 2001). The continuous variable swell height was also recorded on the 1998-2000 cruises.

We explored half-normal and hazard-rate models, each with variable numbers and types of covariates (Forcada 2002). Hazard-rate models gave highly variable estimates of effective strip width among years, and unpublished analyses suggested grounds for biased  $f_{ij}(0, c_{ij})$  estimates using this model in the study data. For consistency we used the half-normal model in each year, with sightings truncated at 5.5km. For each species or stock in each year, covariates were tested singly and in additive combination, and a set of best models was chosen on the basis of Akaike's Information Criterion corrected for sample size ( $AIC_c$ ) (Hurvich and Tsai 1989). For computational efficiency, we retained as reasonable models all models with an  $AIC_c$  difference ( $\Delta AIC$ ) of less than 2 from the best model (Burnham and Anderson 1998). Final estimates of  $f_{ij}(0, c_{ij})$  were produced with model averaging, using the  $AIC_c$  scores as weighting factors. The weight of the estimate from the  $j$ th model was (Burnham and Anderson 1998)

$$w_j = \frac{\exp(-\frac{1}{2} \Delta AIC_j)}{\sum_j \exp(-\frac{1}{2} \Delta AIC_j)}.$$

Strictly speaking, model-averaged estimates are no longer maximum likelihood estimates, but for all of the analyses presented here, they were checked and found to be extremely close.

Pooled abundance components were computed to provide additional summary and diagnostic statistics. Pooled abundance components  $f(0)$ , expected school size  $E(s)$ , school encounter rate  $n/L$ , and percentage of the total abundance estimate due to the prorated abundance of unidentified sightings were calculated across all sightings  $i$  and strata  $j$  as

$$\begin{aligned}
f(0) &= \sum_j \sum_i \hat{f}_{ij}(0, c_{ij}) / \sum_j n_j \\
E(s) &= \sum_j \sum_i \hat{f}_{ij}(0, c_{ij}) \hat{s}_{ij} / \sum_j \sum_i \hat{f}_{ij}(0, c_{ij}) \\
n / L &= \sum_j n_j / \sum_j L_j \\
\% \text{ pro} &= 100 \sum_j \hat{N}_{unid,j} / \sum_j (\hat{N}_{unid,j} + \hat{N}_{id,j})
\end{aligned}$$

for each stock and year, where, for stratum  $j$ ,  $n_j$  was the number of sightings,  $N_{unid,j}$  was the prorated abundance based on unidentified sightings,  $N_{id,j}$  was the abundance based on identified sightings, and other terms were defined above.

### *Unidentified sightings*

Not all sightings could be identified with certainty. The number of sightings recorded as unidentified was first reduced by assigning “probable” sightings of an identified category to that identified category. For the remaining unidentified sightings, we estimated abundance for the unidentified category and prorated the abundance among appropriate stocks in proportion, by stratum, to the estimated abundance from identified sightings of those stocks that were included in the broader unidentified category. The general form of the proration was

$$\hat{N}_{ij} = \hat{N}_{ij}^* + \hat{N}_{uj} \left( \frac{\hat{N}_{ij}^*}{\hat{N}_{ij}^* + \sum_k \hat{N}_{kj}} \right),$$

where  $\hat{N}_{ij}$  was the revised abundance estimate of stock  $i$  in stratum  $j$ ,  $\hat{N}_{ij}^*$  the abundance of stock  $i$  in stratum  $j$  estimated from identified sightings of stock  $i$ ,  $\hat{N}_{uj}$  the abundance of the unidentified category estimated from unidentified sightings in stratum  $j$ , and  $\hat{N}_{kj}$  the abundance of stock  $k$  in stratum  $j$  for stocks other than  $i$  included in the unidentified sighting category.

We estimated abundance of three unidentified sighting categories: unidentified spotted dolphins (prorated to northeastern offshore spotted, western/southern offshore spotted, and coastal spotted dolphins), unidentified spinner dolphins (prorated to eastern spinner and whitebelly spinner dolphins), and unidentified dolphins (prorated among several species, spotted and spinner dolphins among them). For example, to prorate the abundance represented by sightings of unidentified dolphins, we estimated abundance of offshore and coastal spotted dolphins, eastern and whitebelly spinner dolphins, striped dolphins, common dolphins, bottlenose dolphins, rough-toothed dolphins and Risso’s dolphins in each stratum, and distributed the abundance of unidentified dolphins proportionally among them.

### *Precision*

Measures of precision were estimated by balanced nonparametric bootstrap (Davison and Hinkley 1997). Within each stratum, a bootstrap sample was constructed by sampling transects (days on effort) with replacement until the same number of transects had been achieved. To

include the variability due to the school size calibration procedure in the bootstrap, for each school  $s_{ij}$  in the bootstrap sample, the logarithm of a new school size was chosen from a normal distribution with mean  $\ln(s_{ij})$  and variance  $\text{var}[\ln(s_{ij})]$ , equivalent to the estimated variance of the sighting's school size estimate obtained by calibration. For each bootstrap sample, the full estimation procedure was carried out, including proration and model averaging. Models for  $f_{ij}$  ( $0, c_{ij}$ ) estimation were restricted to the set of models with  $\Delta\text{AIC}_c$  less than or equal to 2, based on the original data, plus the univariate half-normal model. From 1000 bootstrap estimates, the standard error, coefficient of variation (CV) and 95%  $\text{BC}_a$  (bias corrected and accelerated, Efron and Tibshirani (1993)) confidence interval of the estimate of total abundance and pooled abundance components were computed.

### *Trend estimation*

To test for trends in the time-series, weighted first- and second-order linear models were fit to the estimates of northeastern offshore spotted and eastern spinner dolphins, using the inverse of the variance of each point estimate as the weighting factor. The statistical significance of each model was tested against the null hypothesis of no change in population size with time, using a Type 1 error rate of  $\alpha = 0.05$ . The statistical power ( $1 - \text{Type 2 error rate}$ ) of detecting a growing population, given the actual number of estimates and their mean precision, was evaluated for simple exponential growth, using a modified version of a program to estimate power for linear regression (Gerrodette 1993). In estimating power, a two-tailed test of significance with  $\alpha = 0.05$  was assumed, and power was calculated for rates of growth from 1% to 5% using the mean CV for northeastern offshore spotted dolphins. To provide visual summaries of the time-series, the estimates were smoothed with nonparametric loess smoothers, using the same inverse-variance weights.

## **RESULTS**

### *Sightings and effort*

For each year in 1998-2000, the ships began the survey on or about July 28 and returned on or about December 9. A good geographic distribution of effort was achieved in the core stratum; effort in the large outer stratum was sparse (Fig. 4). Restricting effort to conditions of Beaufort  $< 6$  and visibility  $> 4$  km resulted in a loss of about 1% of the effort and  $< 1\%$  of the sightings. Under these conditions, transect effort was about 42,000 km in 1998 (with three ships), and 30,000 km each in 1999 and 2000 (Table 1). The total number of transects was 306, 208 and 202 in 1998, 1999 and 2000, respectively (Table 1). By design, more effort was concentrated in the core stratum in 1998-2000 compared to previous years (Fig. 4). The number of sightings of offshore spotted and eastern spinner dolphins was correspondingly higher, particularly in 1998 when three ships were used (Table 2). During the 1986-1990 cruises, total search effort ranged from about 24,000 to 30,000 km each year (Table 1), similar to the 1998-2000 surveys. Effort and number of sightings in 1983 and earlier were less (Tables 1 and 2). The allocation of search effort to a coastal stratum in 1998-2000 (Figs. 2 and 4) resulted in a sufficient number of sightings of the coastal form of spotted dolphins (Table 2).

In addition to the identified sightings in Table 2, there was a large number of unidentified dolphin sightings each year. An unidentified dolphin sighting could potentially be any of a number of species, including spotted and spinner dolphins. Unidentified dolphin sightings were usually small groups of animals seen at a large radial distance from the ship that subsequently could not be relocated, or groups seen at  $>5.6$  km from the trackline that were not approached for identification. Although the number of unidentified dolphin sightings was large, the contribution of these sightings to total abundance was not large because many of the sightings were beyond the truncation distance of 5.5 km, because group size was small, and because only a fraction of the estimated unidentified dolphin abundance was assigned to the stocks of interest.

#### *Model selection, effective strip width, and group size*

A variety of covariates were important in modeling the probability of detecting schools of spotter and spinner dolphins (Table 3). The number of plausible models ( $\Delta AIC \leq 2$ ) ranged from 1 to 5, with multiple models chosen in most years. The traditional univariate model with perpendicular distance as the only predictor was chosen as the best model in about half the cases, but it was never the only model chosen. The number of covariates selected ranged from 1 to 3, with group size being the most frequently selected covariate. Neither stock nor stratum was a significant predictor in any year, given the other variables in the model, so sightings of all stocks within species were combined for  $f_{ij}(0, c_{ij})$  estimation.

The annual number of sightings on which to estimate the detection function ranged from 38 to 310 for spotted dolphins and from 28 to 146 for spinner dolphins. The lowest numbers of sightings occurred in 1980, 1982 and 1983, when the amount of survey effort was small. In these 3 years, therefore, we combined spotted and spinner sightings for  $f_{ij}(0, c_{ij})$  estimation. In other years we treated the sightings of spotted and spinner dolphins separately, and different models were generally selected (Table 3).

The histograms of frequency of sightings by perpendicular distance for spotted (Fig. 5) and spinner (Fig. 6) frequently showed a spike in the frequency of sightings near the trackline. Fitting the probability density function to this spike with exponential or hazard-rate models gave unreasonable values for the effective strip width. Therefore, we used the half-normal model in all years for both species, with the scale modified by the covariates  $c_{ij}$  for each sighting. The  $f(0)$  values shown in Figs. 5 and 6 were fit with a univariate half-normal model and do not include the effects of the covariates.

Dolphin school sizes were large, highly variable, and had strongly skewed distributions (Fig. 7). Across all years, the mean observed school size was slightly larger for spinner dolphins than for spotted dolphins (122 vs. 114). The school size values shown in Fig. 7 include bias correction due to school size estimation tendencies (the calibration procedure), but do not include bias correction due to the effects of the covariates.

#### *Abundance*

Estimated abundance of northeastern offshore spotted dolphins ranged from 494,268 in 1986 to 953,547 in 1989, while estimated abundance of eastern spinner dolphins ranged from

271,322 in 1980 to 741,867 in 1989 (Table 4, Fig. 8). Estimates of abundance for the coastal spotted dolphin were possible by year only in the most recent (1998-2000) surveys, and ranged from 96,738 to 228,038 (Table 4). Coefficients of variation (CVs) ranged from 13.5% to 35.4% for northeastern offshore spotted dolphins, from 21.8% to 40.3% for eastern spinner dolphins, and from 34.3% to 38.6% for coastal spotted dolphins. In general, estimates were more precise in the recent (1998-2000) surveys than in the earlier surveys, and estimates of northeastern offshore spotted dolphins were more precise than estimates of eastern spinner dolphins (Table 4, Fig. 8). Estimates of coastal spotted dolphins had the highest CVs, which were clearly related to the low number of sightings of this stock (Table 2). For all stocks, the bootstrap distributions of abundance estimates were skewed in most years with longer tails of higher values, so that the point estimates were usually below the mid-points of the confidence intervals (Fig. 8), and the distributions could be approximated by a lognormal distribution.

Estimates of pooled abundance components indicated the contribution of effective strip width, school size, encounter rate and proration of unidentified sightings to each abundance estimate (Table 4). Annual  $f(0)$ s ranged from 0.25 to 0.46  $\text{km}^{-1}$ , implying effective half-strip widths of 2-4 km. Averaged across years, the effective strip width was 3.1 km on each side of the trackline for both spotted and spinner dolphins. Annual mean school sizes, corrected for bias due to school size and other sighting covariates as well as bias due to individual observer estimation tendency, ranged from 62 to 220 for northeastern offshore spotted, from 73 to 151 for eastern spinner, and from 66 to 98 for coastal spotted dolphins. The average of these annual means was 108.5, 109.3, and 79.4 for the three stocks, respectively. Encounter rates were 0.385 to 0.934 schools per 100 km for northeastern offshore spotted dolphins, 0.141 to 0.333 for eastern spinner dolphins, and 0.074 to 0.142 for coastal spotted dolphins. The contribution of unidentified sightings to the estimated abundance of each stock varied by year, but averaged 4.5% for northeastern offshore spotted, 4.8% for eastern spinner and 13.4% for coastal spotted dolphins.

### *Trend estimation*

Weighted first-order linear regressions indicated slight positive but statistically insignificant increases for both northeastern offshore spotted ( $P=0.68$ ) and eastern spinner ( $P=0.94$ ) dolphins over the period 1979-2000 (Fig. 9). The estimated increments were about 0.3%/year for northeastern spotted and 0.1%/year for eastern spinner dolphins. Second-order (quadratic) regressions indicated a concave-upward curve for northeastern offshore spotted dolphins, and a concave-downward curve for eastern spinner dolphins, but neither of these was statistically significant at the  $\alpha=0.05$  level ( $P=0.49$  and  $P=0.10$ , respectively; Fig. 9). A weighted loess smooth with span 1.5 through the northeastern offshore spotted estimates indicated a slight decline through the late 1980s and a slight increase ( $<1\%$ /year) since then (Fig. 10). A similar smooth through the eastern spinner estimates indicated an increasing population until 1990 followed by a decline of 2-3%/year until 2000 (Fig. 10).

Given the number of estimates and the observed sampling variances, the probability (statistical power) of detecting a 1%, 2%, 3%, 4%, or 5% annual growth of a population between 1979 and 2000 was estimated to be 0.26, 0.67, 0.95, 1.0 and 1.0, respectively.

## DISCUSSION

### *Abundance*

Based on averages of the three most recent surveys, the current size of the northeastern offshore spotted dolphin population is about 640,000 animals, and the current size of the eastern spinner dolphin population is about 450,000 animals. Both stocks are distributed over large areas in the eastern tropical Pacific Ocean. The estimates from the three most recent surveys agreed well with each other for these stocks within the precision of the estimates (CVs of about 17% and 23%, respectively). The estimates for the coastal spotted dolphin population were less consistent. The average of the three estimates was about 140,000, but the estimates ranged from 97,000 to 228,000 with CVs around 35%. More survey effort near the coast is needed to obtain more precise estimates of abundance for coastal spotted dolphins. Recent studies have indicated that there are several genetically different coastal spotted dolphin stocks (Escorza-Treviño et al. 2002). The estimates presented in this paper do not distinguish among these stocks.

### *Trends*

The estimates of northeastern offshore spotted and eastern spinner dolphins did not show any statistically significant change, either upwards or downwards, during the 21-year period covered in this analysis (Fig. 9). The power analysis showed that if the dolphin populations had been growing (or declining) at a rate of 3% or more per year from 1979-2000, there would have been a high probability ( $>0.95$ ) of detecting that change. It is unlikely, therefore, that either the northeastern offshore spotted or eastern spinner dolphin population was changing at a rate of 3%/year or more during this period. The power analysis indicated an intermediate probability (0.67) of detecting a 2%/year change. This meant that the data suggested that the growth rate was not as high as 2%/year, but that the data did not conclusively support such a conclusion. The low power (0.26) to detect a 1%/year change meant that the data were not informative about whether a change as small as 1%/year was taking place or not. There was no indication for either stock of a recovery since the early 1990s, when the reported bycatch in the tuna purse-seine fishery declined dramatically (Hall and Lennert 1997). The nonparametric smoothed trend lines indicated a slight increase ( $<1\%$ /year) during the last decade for northeastern offshore spotted dolphins, and a slight decrease (2-3%/year) during the same period for eastern spinner dolphins (Fig. 10).

Trends in abundance for these dolphin populations have also been tracked by indices of relative abundance estimated from data collected by observers on tuna vessels. To aid in the comparison of fishing vessel indices with the estimates given in this paper, smoothed lines using weighted loess smoothers for each index have been computed using the same smoothing span as for research vessel estimates (Fig. 11). For the northeastern offshore spotted dolphin stock, several versions of the index have been proposed, including estimates based on a univariate half-normal model (Lennert-Cody et al. 2001), a modes-of-search model which stratified data according to searching method (Lennert-Cody et al. 2001), and a sighting-covariate model (Marques 2001). For this stock, all fishing vessel indices showed an increasing population through about 1990, followed by a decline (Fig. 11). In contrast, the research vessel estimates (this paper) did not indicate a decline in the last decade. For eastern spinner dolphins, the fishing

vessel index was based on the half-normal model only, and showed a similar trajectory to the estimates reported in this paper (Fig. 11). For all estimates derived from fishing vessel data, Lennert-Cody et al. (2001) have shown that the data contain time-varying biases, and they cautioned against use of these indices in population models. However, the same authors also argued that the indices could be used as a rough guideline to the state of the stocks, and concluded that it was unlikely that either of these populations was recovering at the expected rate in the last decade.

### *Responsive movement and detection near the trackline*

This analysis assumed that all dolphin schools on or near the trackline were detected. For spotted and spinner dolphins, this appeared to be satisfied to a close approximation. Previous studies have indicated that while dolphins react to an approaching ship, they are usually detected before any strong reaction occurs (Au and Perryman 1982, Hewitt 1985). During the 1998-2000 cruises, a tally of dolphin sightings missed by marine mammal observers but seen by bird observers indicated that the marine mammal observers detected 96.5% of all dolphin sightings within 300m of the trackline (Brandon et al. 2002). This was reasonable considering that the dolphins tended to occur in medium to large schools, individual dolphins did not have long dive times, and diving was not synchronous among individuals in a school. Therefore, it is likely that some members of the school were at the surface at all times.

Brandon et al. (2002) also examined responsive movement of dolphins on the line-transect surveys. Movement in response to the survey vessel was measured by following schools of dolphins with a helicopter before and after detection by shipboard observers, by using an independent observer at a higher vantage point on the ship who tracked schools before and after detection by the other observers, and by measuring school swim direction and speed from multiple sightings of the school. For spotted and spinner dolphins, there was no consistent pattern of movement either toward or away from the trackline before the dolphin school was detected.

### *Differences from previous estimates*

The estimates of northeastern offshore spotted and eastern spinner dolphin abundance presented in Table 4 differed from past estimates. Although some estimates were higher and others lower, the main feature was that the revised estimates presented here were less variable among years than previously estimated. The differences between the old and new estimates were due to a number of changes, updates and improvements, both to the data and to the analysis. These included: (1) explicit modeling of other factors (covariates) that affected probability of detection; (2) implicit handling of school size detection bias; (3) AIC-weighted averaging of estimates from different models; (4) use of the half-normal model across all years; (5) bias correction of school size estimates based on aerial photography; (6) improved measurements of distance and area; (7) improved bootstrap procedures for estimating variance; and (8) additional checking and editing of data for all years (Jackson 2001).

Covariate modeling. Previous estimates for 1998 (Gerrodette 1999) and 1999 (Gerrodette 2000) and for 1979-1990 (Wade 1994) were based on conventional line-transect

methods. Those methods used perpendicular distance from the trackline to estimate an effective strip width, and relied on “pooling robustness” to account for the multiple factors affecting whether a dolphin school was detected or not (Buckland et al. 1993). While widely used and generally robust, these methods have limitations, and direct modeling of the effects of the other factors is an improved approach (Buckland et al. 2001, Marques 2001, Forcada 2002). For the dolphins considered here, the effects of covariates such as school size, sea state and sighting cue were important in modeling the probability of detection (Table 3). Although requiring the estimation of additional parameters, the inclusion of covariates reduced bias (Forcada 2002) and thus probably contributed to the reduction in variability of the estimates among years.

Group size bias. Conventional line-transect analyses estimate mean group size as one component of the abundance estimator. There are several regression techniques for dealing with the bias that arises because large groups are more easily detected than small groups (Buckland et al. 1993, Forcada 2002). In this analysis, school size was modeled as a covariate of the detection process, so use of these regression techniques to estimate mean group size was not necessary. Bias in observed school sizes was implicitly handled in the model. Further, the covariate model allowed total group size to be modeled when the species of interest formed only part of a mixed-species group, an important consideration for these dolphin species that commonly occurred in mixed-species schools. It was likely that the total size of the school, rather than the subgroup of the species of interest, was the important factor affecting the probability of detection.

Model averaging. The estimates also benefited from model-averaging. In the present case, the likelihood functions indicated that several different covariate models could fit the data in most years reasonably well. The estimates of abundance from these different models were usually quite similar. However, by computing AIC-weighted estimates, the contributions of all the plausible models were taken into account.

Single base model. Decreased variability in the estimates among years was also due to the use of the half-normal distribution to model the detection function for the entire set of estimates. Previous estimates from 1979-1990 (Wade and Gerrodette 1993, Wade 1994) were based on a hazard-rate model, or from a mix of hazard-rate and half-normal models with additional adjustment functions (Gerrodette 1999, 2000). The hazard-rate model has a tendency to overfit spikes in the frequency of sightings near the trackline, which was the case with these data. Lennert-Cody et al (2001) used the half-normal model in preference to the hazard-rate model to reduce the tendency to fit a spike near the trackline for dolphin sightings from tuna vessels.

School size estimation. The calibration procedure for adjusting observers’ school size estimates based on aerial photographs had an important effect on the estimates of abundance. Previous estimates for 1979-1990 (Wade 1994) and for 1998 and 1999 (Gerrodette 1999, 2000) included bias correction, but the present analysis used an expanded and updated set of coefficients based on counts from aerial photographs through 2000, and slightly different statistical models and criteria for model selection (Gerrodette et al. 2002). The present analysis also applied corrections to observers’ estimates over the whole time series; previous estimates did not include corrections prior to 1987 when the aerial calibration program began. Applying corrections to the school size estimates had the effect of increasing estimated abundance.

Analyses with school size corrections gave estimates about 25% higher than analyses without these corrections.<sup>1</sup>

Distance and area measurements. Estimation of abundance in distance sampling is based on measurements of distance to the sighted objects. In this study, distance to marine mammal sightings was estimated by measuring the angle between the horizon and the animals using a reticle scale in a 25-power binocular. Compared to previous analyses, distances used in the present analysis were changed due to improved reticle-to-angle conversions (Kinzey and Gerrodette 2001) and to improved angle measurements accounting for the refraction of light (Kinzey et al. 2002). Both of these adjustments had the effect of increasing the estimated radial distances to sightings slightly, and hence of lowering estimated dolphin abundance slightly throughout the time series. In addition, algorithms used to compute distance between two geographic positions (used to calculate effort) and to compute the area enclosed by a series of positions on the earth's surface were checked and improved (T.G. unpublished data). Changes to length of transect effort and area directly affected the estimates. For example, the calculated size of the core area (Fig. 2) was several percent larger than the equivalent area given in Holt and Sexton (1989) for the 1986-1990 surveys (an exact figure is not possible because of the different stratifications). A larger surface area had the effect of increasing estimates of abundance in that stratum by the same amount.

Bootstrap. Estimation of variance and confidence intervals was also improved in several ways. The bootstrap procedure used here included not only the sampling variance by transect, but also variance due to model selection, school size calibration, proration of unidentified sightings, and correlation among strata (and species in 1980, 1982 and 1983) due to pooling for estimation of  $f_{ij}(0, c_{ij})$ . Previous estimates included only sampling variance (Wade 1994) or sampling variance and model selection variance (Gerrodette 1999, 2000). Inclusion of these other sources of variance gave larger but more realistic estimates of variance, so that despite the improvements due to the modeling the effects of covariates, the precision of the estimates, as measured by the CVs, was not increased appreciably for most estimates. The presence of very large but rarely encountered schools made proper estimation of variance difficult. Modeling school size distribution with an adaptive kernel smoother and resampling from this continuous distribution improved the reliability of the variance estimates (Forcada 2002). Finally, estimation of bootstrap confidence limits were improved by using the BC<sub>a</sub> method rather than simple percentiles.

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Table 1. Size of study area (in km<sup>2</sup>) and amount of survey effort (in km), 1979-2000. Strata are shown in Figs. 2 and 3. The distribution of effort is shown in Fig. 4.

|        |      | Stratum    |            |            |           |           |           |
|--------|------|------------|------------|------------|-----------|-----------|-----------|
|        |      | NES area 1 | NES area 2 | NES area 3 | ES area 1 | ES area 2 |           |
| Area   |      | 2,301,771  | 3,895,404  | 371,304    | 2,397,705 | 7,232,073 |           |
| Effort | 1979 | 8,721      | 3,785      | 62         | 9,083     | 4,426     |           |
|        |      |            |            |            |           |           |           |
|        |      | NE spotted | E spinner  |            |           |           |           |
| Area   |      | 6,568,479  | 9,629,768  |            |           |           |           |
| Effort | 1980 | 6,206      | 10,068     |            |           |           |           |
|        | 1982 | 5,771      | 6,762      |            |           |           |           |
|        | 1983 | 4,410      | 4,273      |            |           |           |           |
|        |      |            |            |            |           |           |           |
|        |      | Inshore 1  | Inshore 2  | Middle 1   | Middle 2  | West      | South     |
| Area   |      | 4,603,230  | 1,400,097  | 2,000,128  | 1,809,659 | 5,217,851 | 4,539,451 |
| Effort | 1986 | 9,077      | 2,630      | 3,345      | 4,317     | 3,848     | 3,910     |
|        | 1987 | 8,361      | 2,934      | 4,327      | 3,655     | 3,823     | 4,491     |
|        | 1988 | 7,336      | 2,065      | 3,530      | 2,648     | 3,189     | 5,020     |
|        | 1989 | 9,006      | 2,719      | 4,303      | 3,597     | 3,659     | 4,833     |
|        | 1990 | 7,321      | 2,727      | 4,652      | 4,212     | 5,483     | 6,576     |
|        |      |            |            |            |           |           |           |
|        |      | Core       | Outer      | N Coastal  | S Coastal |           |           |
| Area   |      | 5,869,484  | 14,777,853 | 534,821    | 171,466   |           |           |
| Effort | 1998 | 19,955     | 17,185     | 4,417      | 830       |           |           |
|        | 1999 | 15,797     | 11,820     | 2,002      | 111       |           |           |
|        | 2000 | 15,045     | 11,523     | 2,795      | 635       |           |           |

Table 2. Number of sightings (schools) during periods of searching effort.

| Species |                  | Stratum    |            |            |           |           |       |
|---------|------------------|------------|------------|------------|-----------|-----------|-------|
|         |                  | NES area 1 | NES area 2 | NES area 3 | ES area 1 | ES area 2 |       |
| 1979    | Offshore spotted | 57         | 5          | 0          |           |           |       |
|         | Eastern spinner  |            |            |            | 34        | 1         |       |
|         |                  | NE spotted | E spinner  |            |           |           |       |
| 1980    | Offshore spotted | 45         |            |            |           |           |       |
|         | Eastern spinner  |            | 17         |            |           |           |       |
| 1982    | Offshore spotted | 26         |            |            |           |           |       |
|         | Eastern spinner  |            | 18         |            |           |           |       |
| 1983    | Offshore spotted | 26         |            |            |           |           |       |
|         | Eastern spinner  |            | 15         |            |           |           |       |
|         |                  | Inshore 1  | Inshore 2  | Middle 1   | Middle 2  | West      | South |
| 1986    | Offshore spotted | 67         | 12         | 19         | 17        | 17        | 5     |
|         | Eastern spinner  | 45         | 1          | 16         | 0         | 3         | 0     |
| 1987    | Offshore spotted | 67         | 2          | 24         | 23        | 16        | 12    |
|         | Eastern spinner  | 42         | 0          | 18         | 0         | 2         | 0     |
| 1988    | Offshore spotted | 53         | 4          | 12         | 7         | 16        | 5     |
|         | Eastern spinner  | 36         | 2          | 4          | 0         | 1         | 0     |
| 1989    | Offshore spotted | 78         | 7          | 17         | 16        | 15        | 7     |
|         | Eastern spinner  | 61         | 0          | 15         | 2         | 1         | 0     |
| 1990    | Offshore spotted | 62         | 4          | 19         | 18        | 11        | 8     |
|         | Eastern spinner  | 31         | 0          | 12         | 2         | 2         | 0     |
|         |                  | Core       | Outer      | N Coastal  | S Coastal |           |       |
| 1998    | Offshore spotted | 165        | 47         | 26         | 2         |           |       |
|         | Coastal spotted  | 0          | 0          | 49         | 2         |           |       |
|         | Eastern spinner  | 78         | 8          | 13         | 0         |           |       |
| 1999    | Offshore spotted | 104        | 32         | 6          | 0         |           |       |
|         | Coastal spotted  | 3          | 0          | 19         | 0         |           |       |
|         | Eastern spinner  | 66         | 0          | 4          | 0         |           |       |
| 2000    | Offshore spotted | 107        | 29         | 5          | 0         |           |       |
|         | Coastal spotted  | 0          | 0          | 42         | 0         |           |       |
|         | Eastern spinner  | 63         | 0          | 8          | 0         |           |       |

Table 3. Models for  $f_{ij}(0, c_{ij})$  estimation. Each cell of the table shows the variables (perpendicular distance plus possible covariates) of the model(s), in the order selected by AIC<sub>c</sub>, used with the half-normal model for estimation of  $f_{ij}(0, c_{ij})$  for that species and year. If more than one model is shown, model-averaging was used. Abbreviations are: pd = perpendicular distance, st = stratum, sp = species (stock), gs = group (total school) size, t = time of day, s = ship, bf = Beaufort sea state, sh = swell height, b = birds present, c=sighting cue. Variables within a model are connected with “+”.

|      | Spotted dolphins                           | Spinner dolphins                     |
|------|--|--------------------------------------|
| 1979 | pd, pd+t, pd+gs                            | pd, pd+bf, pd+t                      |
| 1980 | pd+gs                                      | pd+gs                                |
| 1982 | pd, pd+gs, pd+b                            | pd, pd+gs, pd+b                      |
| 1983 | pd, pd+bf                                  | pd, pd+bf                            |
| 1986 | pd+s, pd+s+gl                              | pd, pd+s, pd+b, pd+gl, pd+bf, pd+s+t |
| 1987 | pd+b+bf+gl, pd+b+bf, pd+b, pd+b+t, pd+b+gl | pd+s, pd+s+t, pd+s+bf                |
| 1988 | pd, pd+gl, pd+bf, pd+gs                    | pd, pd+gs, pd+bf                     |
| 1989 | pd+s, pd+s+b, pd+s+gs, pd+s+t              | pd+s, pd+s+gl, pd, pd+s+t            |
| 1990 | pd+gs, pd                                  | pd, pd+gs, pd+bf, pd+b               |
| 1998 | Pd+c                                       | pd, pd+gs                            |
| 1999 | pd+gs, pd, pd+bi, pd+bf                    | pd, pd+gs                            |
| 2000 | pd+gs+t, pd+gs                             | pd, pd+sh, pd+bi, pd+gs              |

Table 4. Estimates and measures of precision for abundance and pooled abundance components.  $N$  = abundance,  $E(s)$  = pooled expected school size,  $f(0)$  = pooled probability density function of detection evaluated at zero perpendicular distance, in  $\text{km}^{-1}$ ,  $n/L$  = pooled encounter rate in schools/km, %pro = pooled percentage of abundance estimate contributed by unidentified sightings, SE = standard error, %CV = coefficient of variation expressed as a percentage, LCL = lower 95% confidence limit, and UCL = upper 95% confidence limit.

| 1979                |           | Estimate | SE      | %CV  | LCL     | UCL       |
|---------------------|-----------|----------|---------|------|---------|-----------|
| NE offshore spotted |           |          |         |      |         |           |
|                     | $N$       | 707,763  | 199,508 | 27.6 | 378,164 | 1,176,016 |
|                     | $f(0)$    | 0.334    | 0.033   | 9.8  | 0.278   | 0.407     |
|                     | $E(s)$    | 219.8    | 30.0    | 13.7 | 161.5   | 277.0     |
|                     | $100*n/L$ | 0.385    | 0.060   | 15.5 | 0.276   | 0.506     |
|                     | %pro      | 5.0      | 2.2     | 36.5 | 2.9     | 11.4      |
| Eastern spinner     |           |          |         |      |         |           |
|                     | $N$       | 449,250  | 169,103 | 35.4 | 199,272 | 842,868   |
|                     | $f(0)$    | 0.310    | 0.051   | 15.6 | 0.244   | 0.449     |
|                     | $E(s)$    | 129.7    | 20.7    | 16.0 | 89.4    | 171.7     |
|                     | $100*n/L$ | 0.222    | 0.063   | 28.5 | 0.109   | 0.353     |
|                     | %pro      | 4.5      | 1.6     | 33.8 | 2.4     | 8.5       |
| 1980                |           | Estimate | SE      | %CV  | LCL     | UCL       |
| NE offshore spotted |           |          |         |      |         |           |
|                     | $N$       | 739,824  | 187,457 | 24.8 | 426,235 | 1,143,982 |
|                     | $f(0)$    | 0.348    | 0.049   | 14.2 | 0.256   | 0.448     |
|                     | $E(s)$    | 94.2     | 12.7    | 13.0 | 73.9    | 123.6     |
|                     | $100*n/L$ | 0.934    | 0.169   | 18.1 | 0.617   | 1.301     |
|                     | %pro      | 12.2     | 5.0     | 39.3 | 5.2     | 24.1      |
| Eastern spinner     |           |          |         |      |         |           |
|                     | $N$       | 271,322  | 106,362 | 38.2 | 91,759  | 506,059   |
|                     | $f(0)$    | 0.324    | 0.050   | 14.9 | 0.248   | 0.448     |
|                     | $E(s)$    | 111.4    | 27.0    | 23.9 | 61.4    | 167.2     |
|                     | $100*n/L$ | 0.141    | 0.048   | 33.9 | 0.061   | 0.247     |
|                     | %pro      | 10.0     | 4.1     | 40.2 | 5.2     | 17.1      |
| 1982                |           | Estimate | SE      | %CV  | LCL     | UCL       |
| NE offshore spotted |           |          |         |      |         |           |
|                     | $N$       | 605,301  | 164,517 | 28.8 | 261,736 | 907,872   |
|                     | $f(0)$    | 0.279    | 0.049   | 15.9 | 0.238   | 0.433     |
|                     | $E(s)$    | 124.0    | 23.4    | 21.6 | 67.7    | 157.1     |
|                     | $100*n/L$ | 0.728    | 0.136   | 18.6 | 0.497   | 1.022     |
|                     | %pro      | 7.0      | 3.1     | 40.0 | 3.2     | 14.8      |
| Eastern spinner     |           |          |         |      |         |           |
|                     | $N$       | 285,192  | 116,596 | 38.7 | 107,145 | 563,274   |
|                     | $f(0)$    | 0.267    | 0.038   | 13.5 | 0.224   | 0.367     |
|                     | $E(s)$    | 86.5     | 22.9    | 26.7 | 43.2    | 133.5     |
|                     | $100*n/L$ | 0.228    | 0.073   | 31.9 | 0.101   | 0.388     |
|                     | %pro      | 11.2     | 4.9     | 41.9 | 5.5     | 22.2      |

| 1983                | Estimate | SE      | %CV  | LCL     | UCL       |
|---------------------|----------|---------|------|---------|-----------|
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 547,637  | 188,609 | 33.5 | 249,541 | 982,805   |
| $f(0)$              | 0.464    | 0.074   | 15.6 | 0.361   | 0.651     |
| $E(s)$              | 62.0     | 11.8    | 18.9 | 41.8    | 86.2      |
| $100*n/L$           | 0.874    | 0.167   | 19.0 | 0.574   | 1.251     |
| %pro                | 3.1      | 1.4     | 42.3 | 1.4     | 6.7       |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 618,749  | 260,857 | 40.3 | 216,737 | 1,218,456 |
| $f(0)$              | 0.446    | 0.070   | 15.1 | 0.358   | 0.629     |
| $E(s)$              | 82.1     | 22.7    | 27.3 | 41.9    | 132.1     |
| $100*n/L$           | 0.333    | 0.101   | 30.2 | 0.155   | 0.547     |
| %pro                | 5.2      | 2.7     | 47.7 | 2.0     | 11.3      |
| 1986                | Estimate | SE      | %CV  | LCL     | UCL       |
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 494,268  | 108,738 | 22.0 | 327,914 | 781,028   |
| $f(0)$              | 0.328    | 0.022   | 6.9  | 0.291   | 0.378     |
| $E(s)$              | 71.8     | 8.8     | 12.3 | 55.7    | 92.2      |
| $100*n/L$           | 0.620    | 0.099   | 15.9 | 0.441   | 0.835     |
| %pro                | 2.1      | 0.8     | 36.7 | 1.0     | 4.1       |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 536,438  | 188,599 | 34.7 | 270,640 | 1,043,375 |
| $f(0)$              | 0.304    | 0.034   | 10.8 | 0.250   | 0.377     |
| $E(s)$              | 92.9     | 21.9    | 24.1 | 65.1    | 160.7     |
| $100*n/L$           | 0.225    | 0.033   | 14.6 | 0.160   | 0.285     |
| %pro                | 4.3      | 3.9     | 84.2 | 1.6     | 26.1      |
| 1987                | Estimate | SE      | %CV  | LCL     | UCL       |
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 501,279  | 99,805  | 19.4 | 335,717 | 729,563   |
| $f(0)$              | 0.304    | 0.021   | 6.9  | 0.269   | 0.349     |
| $E(s)$              | 76.2     | 9.5     | 12.4 | 58.9    | 96.9      |
| $100*n/L$           | 0.623    | 0.104   | 16.8 | 0.461   | 0.856     |
| %pro                | 2.5      | 0.6     | 25.3 | 1.6     | 4.1       |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 442,938  | 122,668 | 30.1 | 266,138 | 838,942   |
| $f(0)$              | 0.382    | 0.045   | 12.9 | 0.327   | 0.512     |
| $E(s)$              | 73.1     | 19.5    | 24.9 | 48.7    | 130.4     |
| $100*n/L$           | 0.196    | 0.041   | 21.2 | 0.133   | 0.307     |
| %pro                | 5.1      | 2.3     | 58.7 | 2.8     | 16.7      |
| 1988                | Estimate | SE      | %CV  | LCL     | UCL       |
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 867,601  | 207,193 | 23.6 | 540,845 | 1,363,024 |
| $f(0)$              | 0.327    | 0.023   | 7.1  | 0.284   | 0.374     |
| $E(s)$              | 139.9    | 17.7    | 12.7 | 108.4   | 178.3     |
| $100*n/L$           | 0.552    | 0.102   | 18.5 | 0.383   | 0.801     |

|                 |         |         |      |         |           |
|-----------------|---------|---------|------|---------|-----------|
| %pro            | 1.9     | 1.0     | 51.0 | 0.7     | 5.0       |
| Eastern spinner |         |         |      |         |           |
| $N$             | 635,572 | 184,308 | 28.0 | 320,892 | 1,028,912 |
| $f(0)$          | 0.349   | 0.052   | 13.9 | 0.289   | 0.429     |
| $E(s)$          | 150.9   | 28.5    | 19.3 | 112.1   | 231.0     |
| $100*n/L$       | 0.160   | 0.040   | 24.9 | 0.097   | 0.254     |
| %pro            | 1.3     | 0.5     | 40.2 | 0.6     | 2.8       |

| 1989                | Estimate | SE      | %CV  | LCL     | UCL       |
|---------------------|----------|---------|------|---------|-----------|
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 953,762  | 234,515 | 23.7 | 582,293 | 1,473,849 |
| $f(0)$              | 0.295    | 0.016   | 5.2  | 0.263   | 0.319     |
| $E(s)$              | 143.7    | 29.3    | 20.0 | 100.6   | 220.7     |
| $100*n/L$           | 0.661    | 0.105   | 15.9 | 0.486   | 0.908     |
| %pro                | 3.1      | 2.8     | 84.1 | 0.6     | 15.9      |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 734,071  | 319,762 | 40.9 | 298,190 | 1,478,920 |
| $f(0)$              | 0.316    | 0.049   | 15.7 | 0.258   | 0.478     |
| $E(s)$              | 131.9    | 34.5    | 26.1 | 84.9    | 235.0     |
| $100*n/L$           | 0.253    | 0.041   | 16.2 | 0.177   | 0.334     |
| %pro                | 3.3      | 2.7     | 80.6 | 0.7     | 17.1      |

| 1990                | Estimate | SE      | %CV  | LCL     | UCL       |
|---------------------|----------|---------|------|---------|-----------|
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 665,835  | 246,270 | 37.1 | 365,824 | 1,537,941 |
| $f(0)$              | 0.254    | 0.020   | 7.8  | 0.212   | 0.292     |
| $E(s)$              | 106.1    | 35.3    | 33.9 | 66.0    | 267.7     |
| $100*n/L$           | 0.660    | 0.104   | 15.7 | 0.479   | 0.876     |
| %pro                | 5.4      | 1.9     | 33.8 | 2.6     | 9.7       |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 459,338  | 135,976 | 29.1 | 251,908 | 803,671   |
| $f(0)$              | 0.300    | 0.035   | 11.4 | 0.253   | 0.396     |
| $E(s)$              | 98.3     | 14.9    | 15.2 | 73.5    | 133.2     |
| $100*n/L$           | 0.145    | 0.027   | 18.5 | 0.098   | 0.203     |
| %pro                | 6.2      | 2.2     | 34.0 | 3.0     | 11.9      |

| 1998                | Estimate | SE     | %CV  | LCL     | UCL     |
|---------------------|----------|--------|------|---------|---------|
| NE offshore spotted |          |        |      |         |         |
| $N$                 | 675,940  | 93,663 | 13.5 | 509,818 | 888,371 |
| $f(0)$              | 0.379    | 0.022  | 5.8  | 0.341   | 0.426   |
| $E(s)$              | 67.8     | 6.2    | 8.8  | 54.8    | 78.0    |
| $100*n/L$           | 0.770    | 0.089  | 11.6 | 0.601   | 0.958   |
| %pro                | 4.9      | 1.4    | 28.5 | 3.1     | 8.8     |
| Coastal spotted     |          |        |      |         |         |
| $N$                 | 106,399  | 34,842 | 34.3 | 44,373  | 177,611 |
| $f(0)$              | 0.456    | 0.052  | 12.5 | 0.378   | 0.607   |
| $E(s)$              | 66.2     | 22.1   | 30.8 | 31.9    | 109.7   |
| $100*n/L$           | 0.120    | 0.029  | 24.5 | 0.073   | 0.193   |
| %pro                | 8.9      | 4.3    | 48.5 | 3.8     | 24.8    |

|                 |         |         |      |         |         |
|-----------------|---------|---------|------|---------|---------|
| Eastern spinner |         |         |      |         |         |
| $N$             | 557,028 | 126,804 | 22.1 | 361,874 | 854,267 |
| $f(0)$          | 0.337   | 0.024   | 7.2  | 0.287   | 0.386   |
| $E(s)$          | 123.4   | 15.3    | 12.2 | 97.3    | 157.3   |
| $100*n/L$       | 0.225   | 0.036   | 15.8 | 0.165   | 0.308   |
| %pro            | 2.5     | 0.5     | 20.5 | 1.7     | 3.8     |

| 1999                | Estimate | SE     | %CV  | LCL     | UCL     |
|---------------------|----------|--------|------|---------|---------|
| NE offshore spotted |          |        |      |         |         |
| $N$                 | 600,299  | 93,793 | 16.5 | 400,912 | 762,844 |
| $f(0)$              | 0.293    | 0.020  | 6.6  | 0.254   | 0.325   |
| $E(s)$              | 95.9     | 8.9    | 10.0 | 85.4    | 119.0   |
| $100*n/L$           | 0.603    | 0.086  | 14.2 | 0.461   | 0.821   |
| %pro                | 4.5      | 1.4    | 29.6 | 2.6     | 8.3     |
| Coastal spotted     |          |        |      |         |         |
| $N$                 | 96,738   | 37,050 | 38.6 | 32,849  | 177,302 |
| $f(0)$              | 0.296    | 0.046  | 13.2 | 0.244   | 0.345   |
| $E(s)$              | 74.4     | 28.3   | 41.8 | 45.2    | 301.3   |
| $100*n/L$           | 0.074    | 0.027  | 36.3 | 0.034   | 0.149   |
| %pro                | 8.6      | 3.8    | 44.7 | 3.5     | 20.7    |
| Eastern spinner     |          |        |      |         |         |
| $N$                 | 361,209  | 89,315 | 24.8 | 196,494 | 534,080 |
| $f(0)$              | 0.278    | 0.025  | 8.6  | 0.228   | 0.315   |
| $E(s)$              | 107.2    | 19.6   | 19.0 | 79.8    | 174.1   |
| $100*n/L$           | 0.227    | 0.045  | 19.8 | 0.161   | 0.348   |
| %pro                | 2.9      | 0.8    | 26.8 | 1.7     | 4.8     |

| 2000                | Estimate | SE      | %CV  | LCL     | UCL       |
|---------------------|----------|---------|------|---------|-----------|
| NE offshore spotted |          |         |      |         |           |
| $N$                 | 647,218  | 151,039 | 20.6 | 459,224 | 1,039,785 |
| $f(0)$              | 0.301    | 0.021   | 6.6  | 0.275   | 0.355     |
| $E(s)$              | 100.9    | 14.2    | 13.0 | 84.1    | 137.3     |
| $100*n/L$           | 0.601    | 0.086   | 14.3 | 0.441   | 0.794     |
| %pro                | 2.7      | 1.0     | 37.2 | 1.1     | 5.1       |
| Coastal spotted     |          |         |      |         |           |
| $N$                 | 228,038  | 87,193  | 34.3 | 72,332  | 392,756   |
| $f(0)$              | 0.348    | 0.038   | 11.4 | 0.282   | 0.434     |
| $E(s)$              | 97.5     | 41.9    | 36.1 | 57.7    | 212.6     |
| $100*n/L$           | 0.142    | 0.049   | 34.6 | 0.058   | 0.246     |
| %pro                | 22.6     | 8.8     | 37.8 | 7.0     | 41.4      |
| Eastern spinner     |          |         |      |         |           |
| $N$                 | 427,587  | 95,358  | 21.8 | 255,462 | 638,913   |
| $f(0)$              | 0.301    | 0.024   | 7.7  | 0.267   | 0.358     |
| $E(s)$              | 124.3    | 23.9    | 19.3 | 86.4    | 176.2     |
| $100*n/L$           | 0.227    | 0.039   | 17.2 | 0.150   | 0.305     |
| %pro                | 1.0      | 0.2     | 24.6 | 0.6     | 1.5       |



Fig. 1. The eastern tropical Pacific and the approximate ranges of the dolphin populations considered in this report.

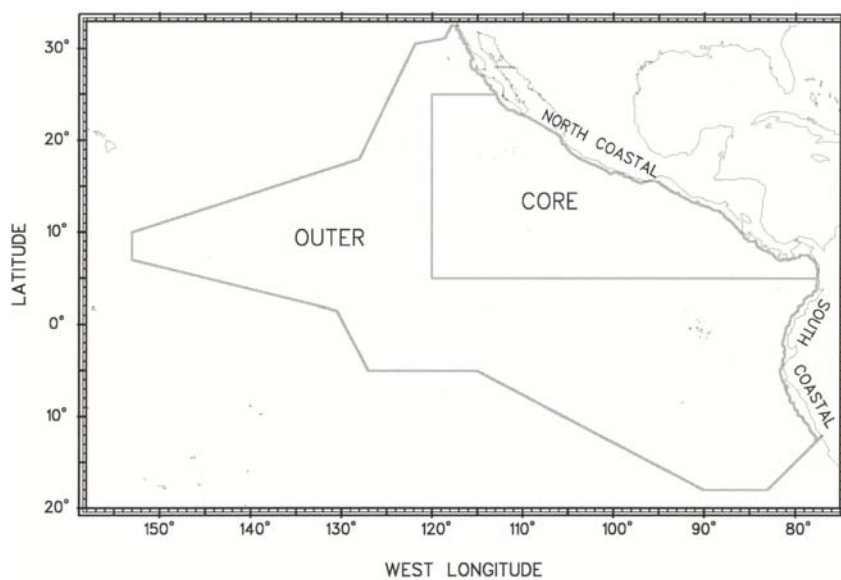


Fig. 2. Strata used in the 1998-2000 surveys.

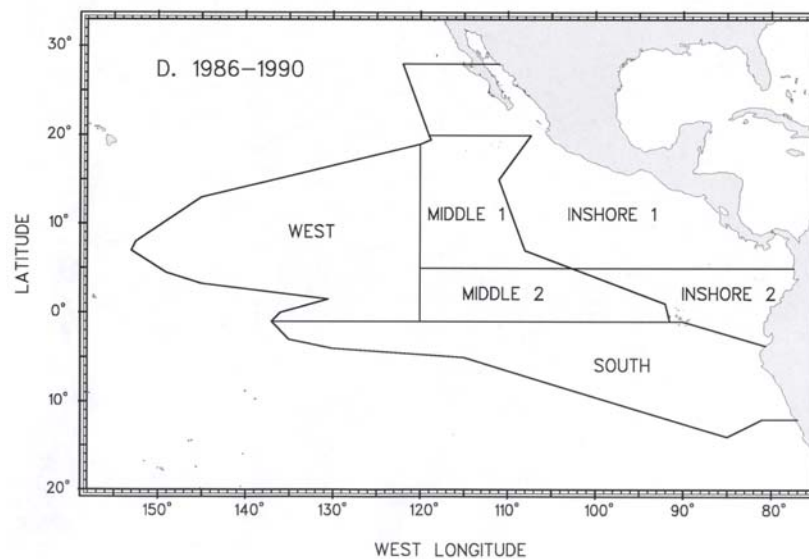
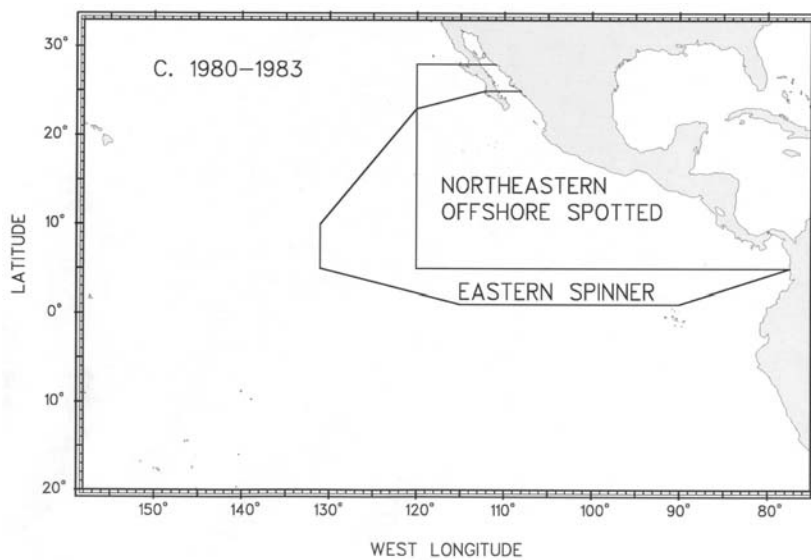
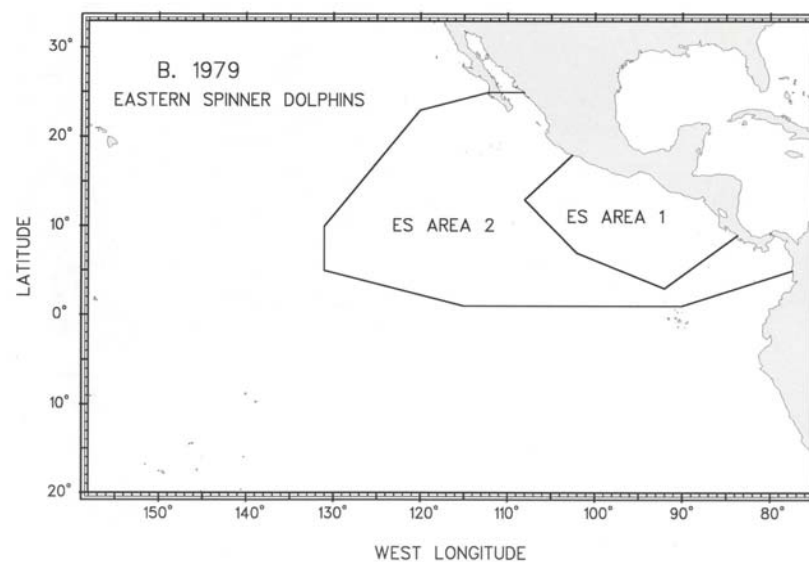
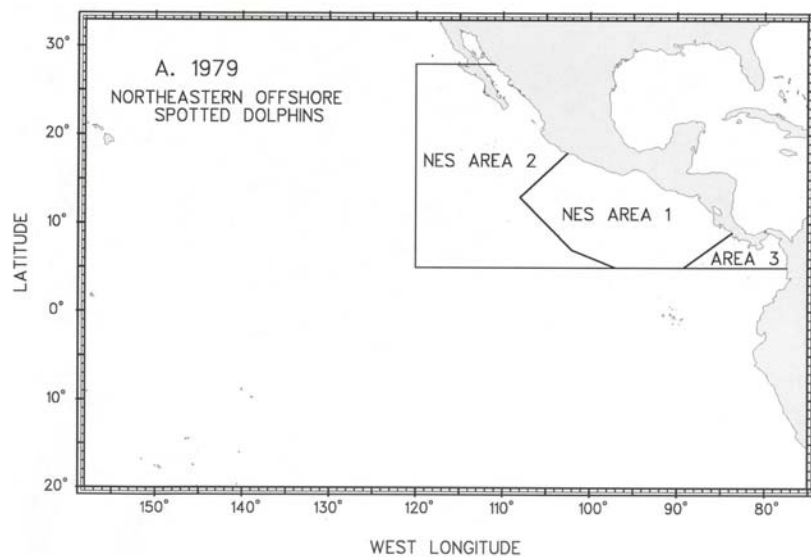


Fig. 3. Strata used in surveys prior to 1998. (A) 1979 survey, spinner dolphins; (C) surveys in 1980, 1982 and 1983; (D)

northeastern offshore spotted dolphins; (B) 1979 survey, eastern surveys in 1986-1990.

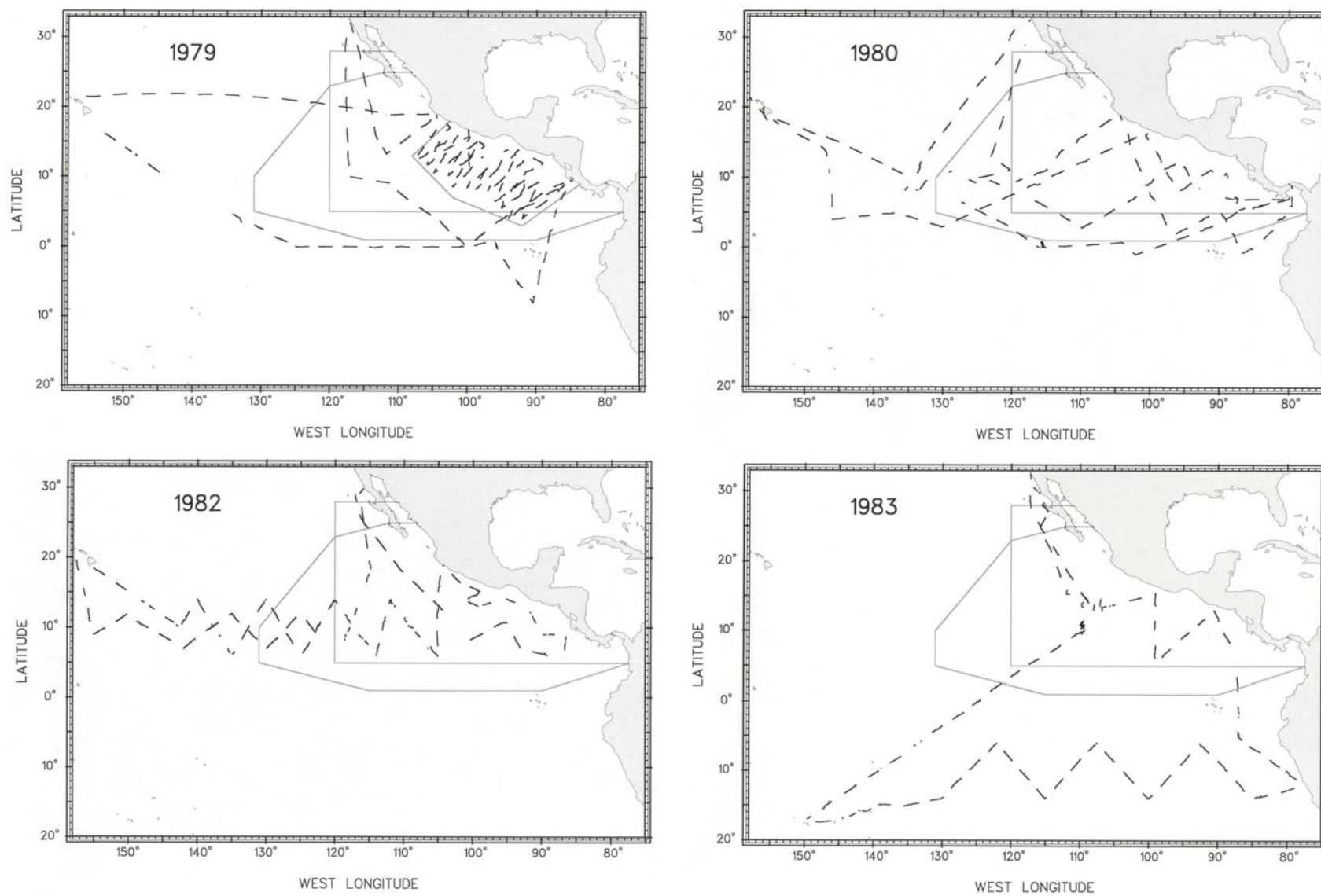


Fig. 4. Tracklines of search effort for cruises in 1979, 1980, 1982 and 1983.

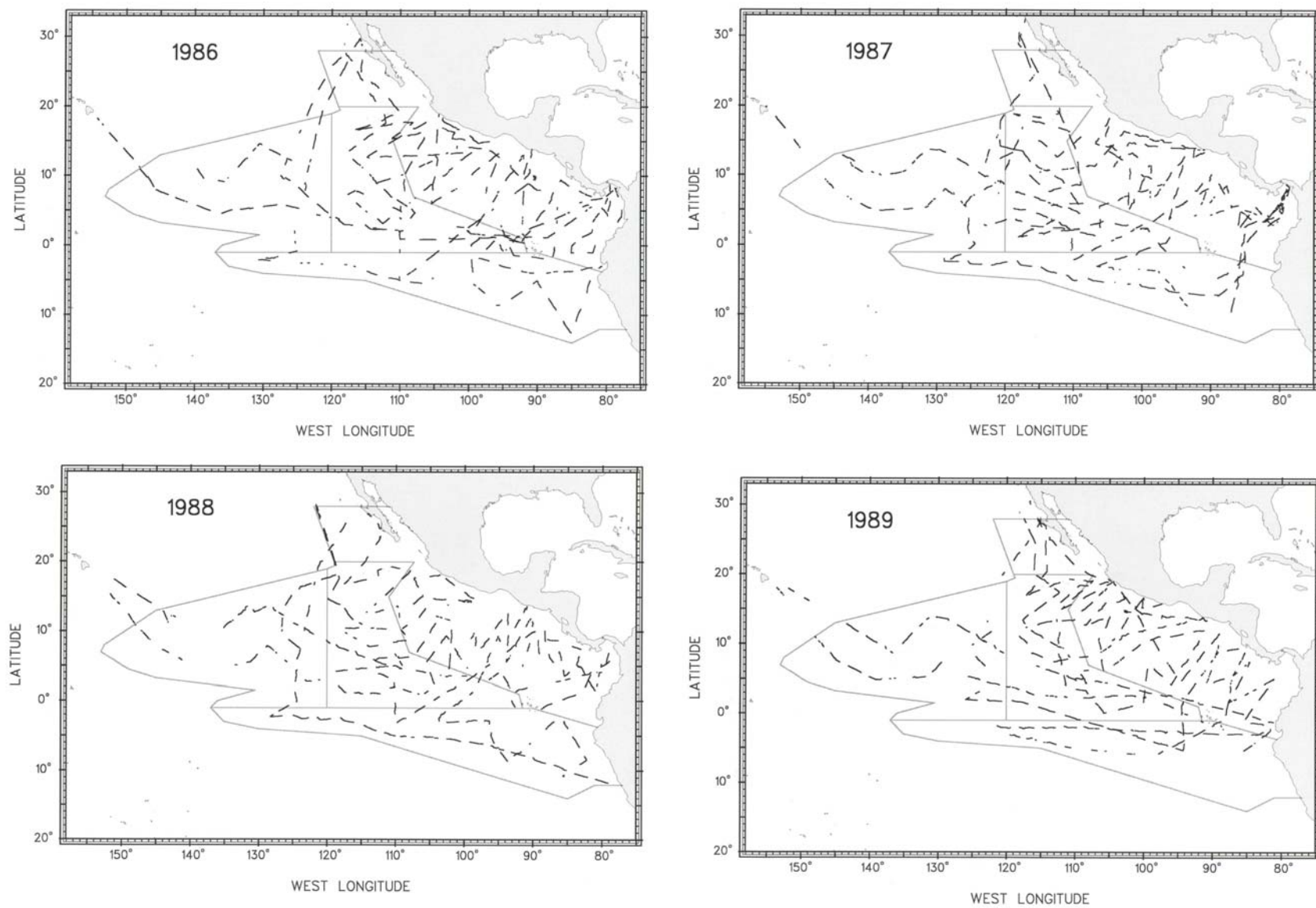


Fig. 4 (cont'd). Tracklines of search effort for cruises in 1986, 1987, 1988 and 1989.

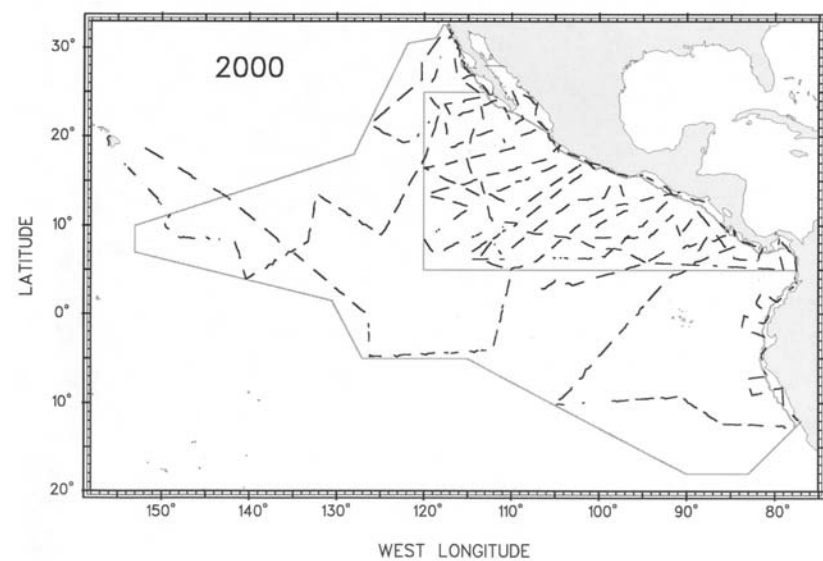
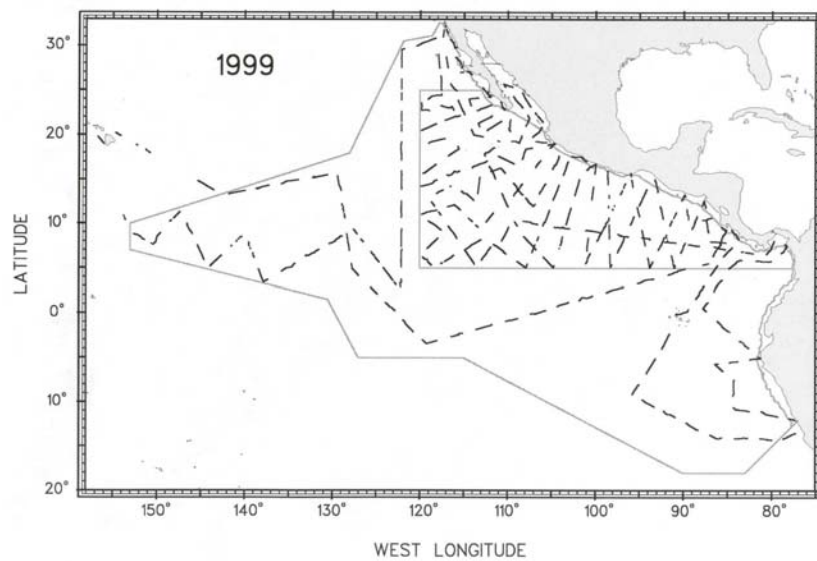
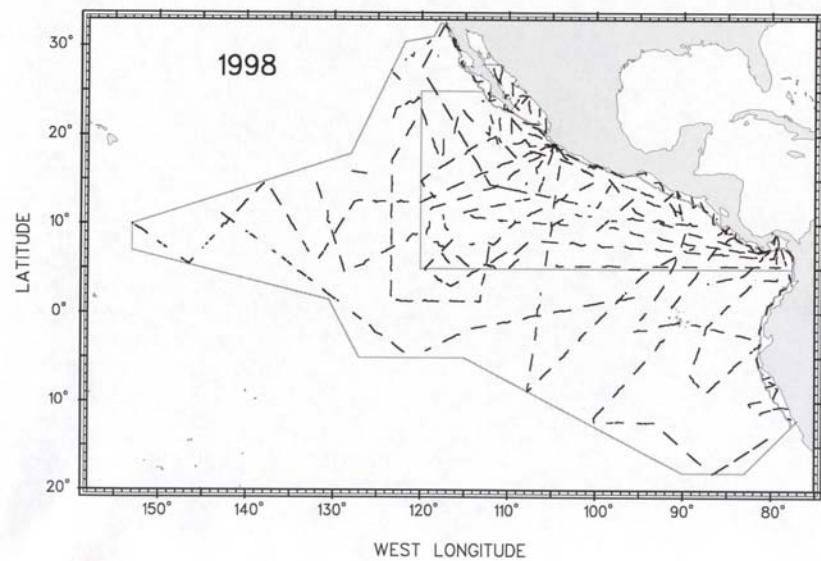
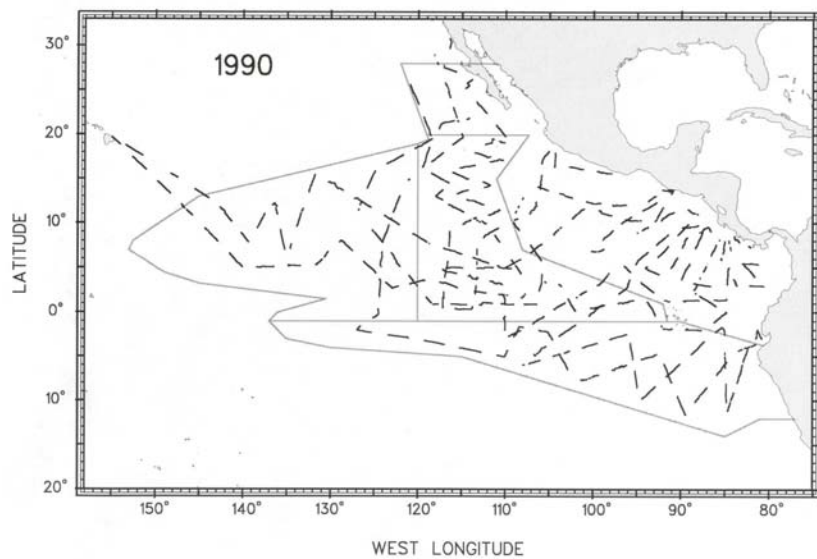


Fig. 4 (cont'd). Tracklines of search effort for cruises in 1990, 1998, 1999 and 2000.

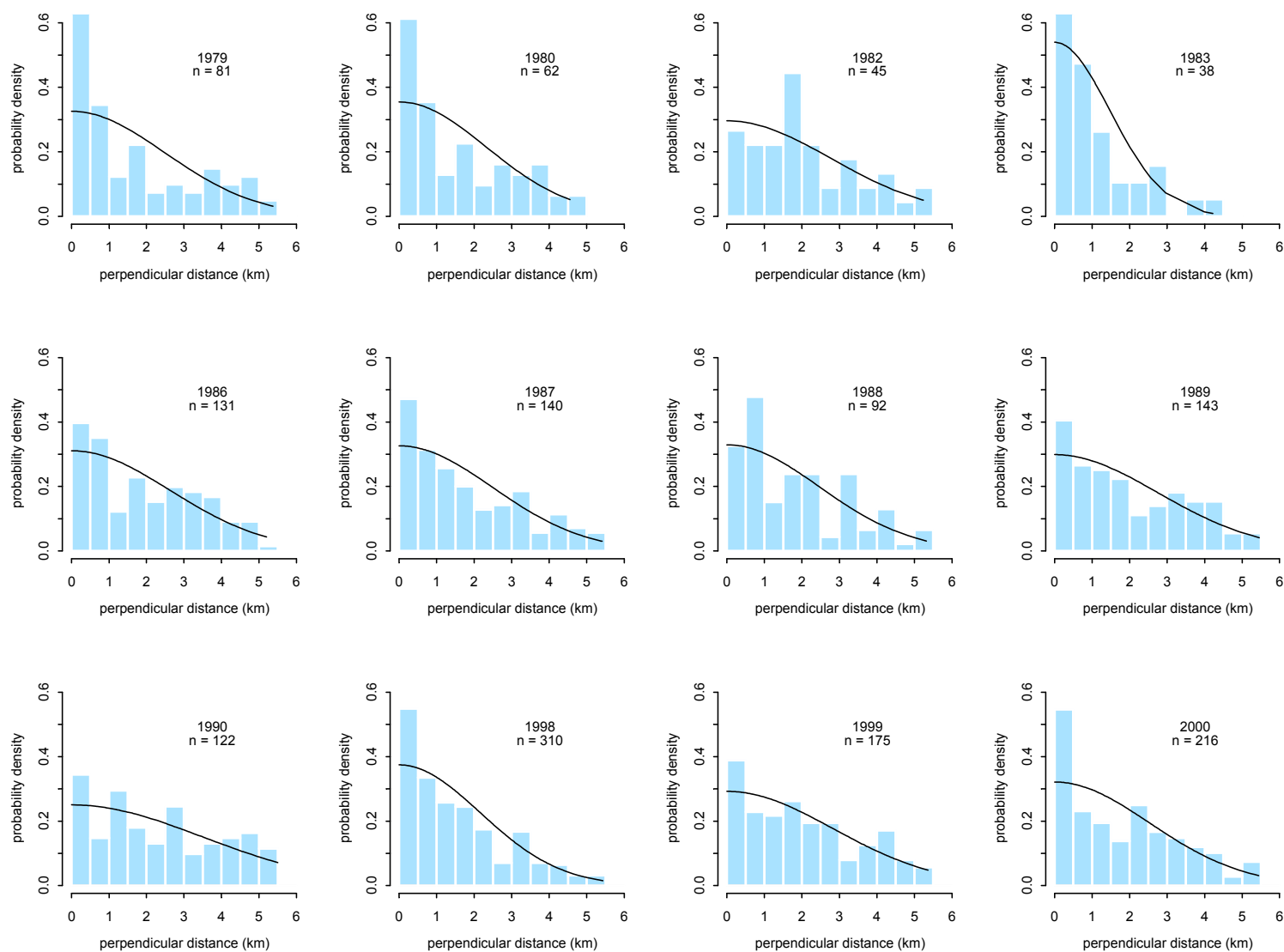


Fig. 5. Histograms of frequency of sightings by perpendicular distance for spotted dolphins. A half-normal model fitted to the observations (without covariates) is shown for each year.

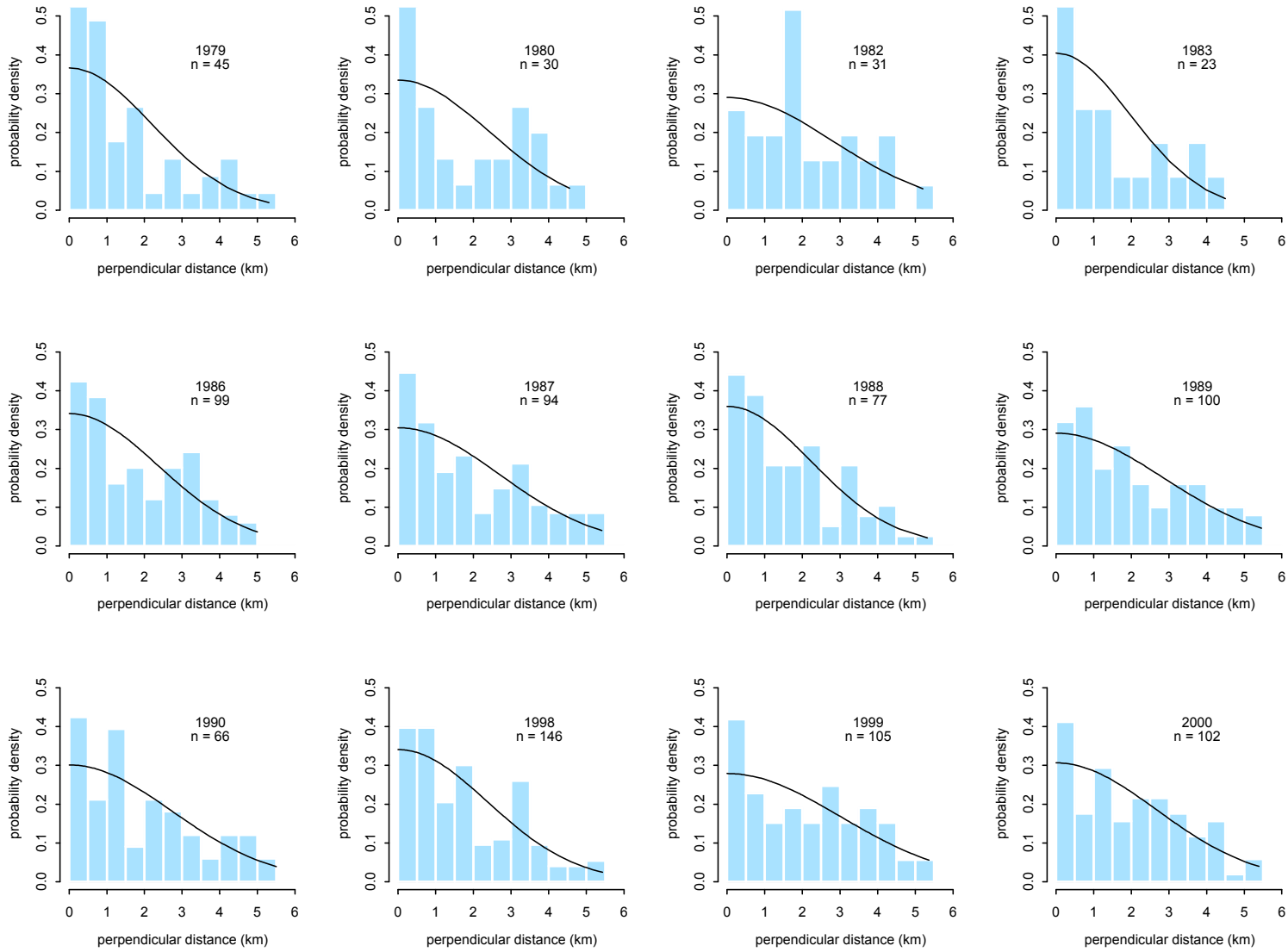


Fig. 6. Histograms of frequency of sightings by perpendicular distance for spinner dolphins. A half-normal model fitted to the observations (without covariates) is shown for each year.



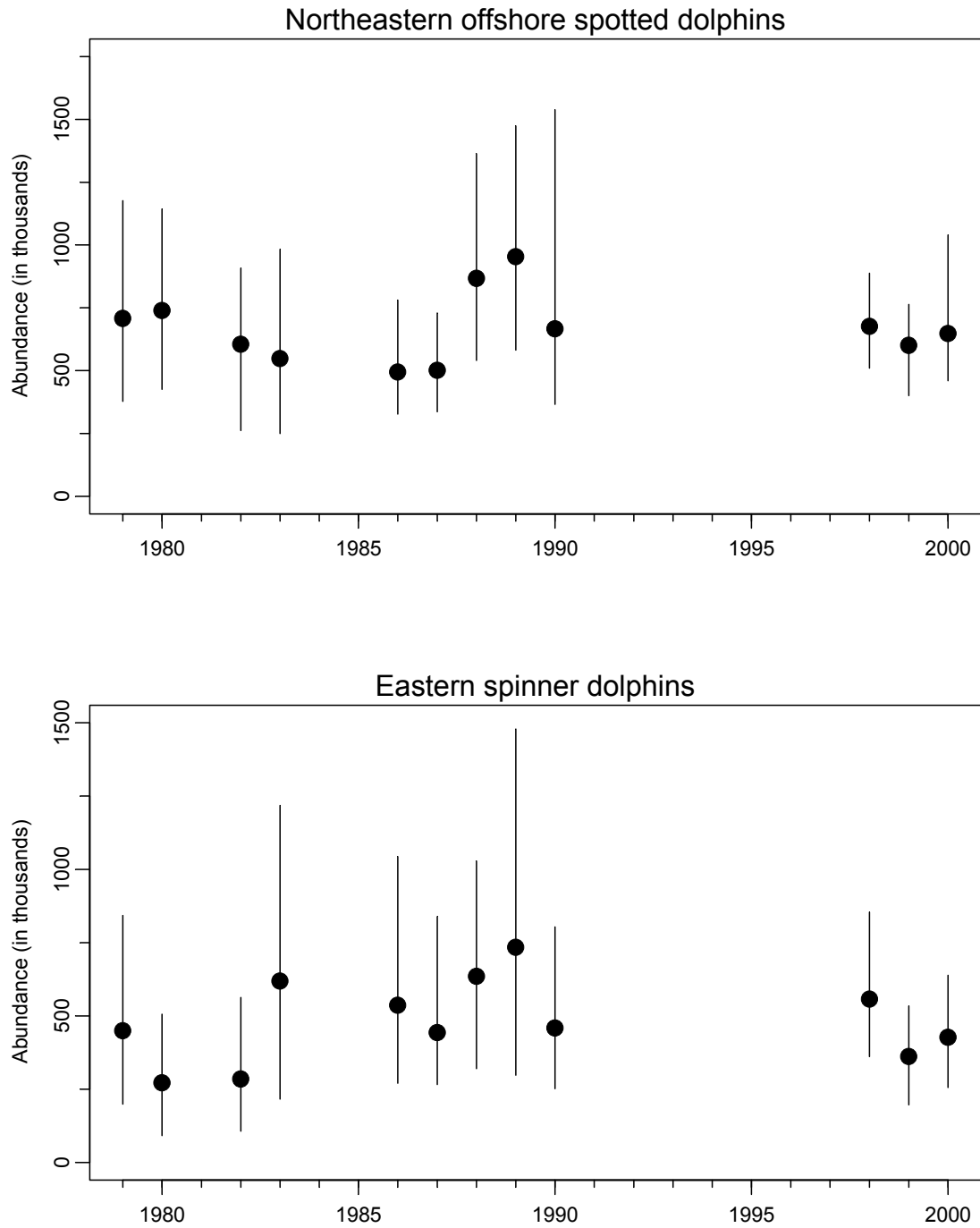


Fig. 8. Estimates of abundance for northeastern offshore spotted and eastern spinner dolphins, 1979-2000, with 95% confidence intervals.

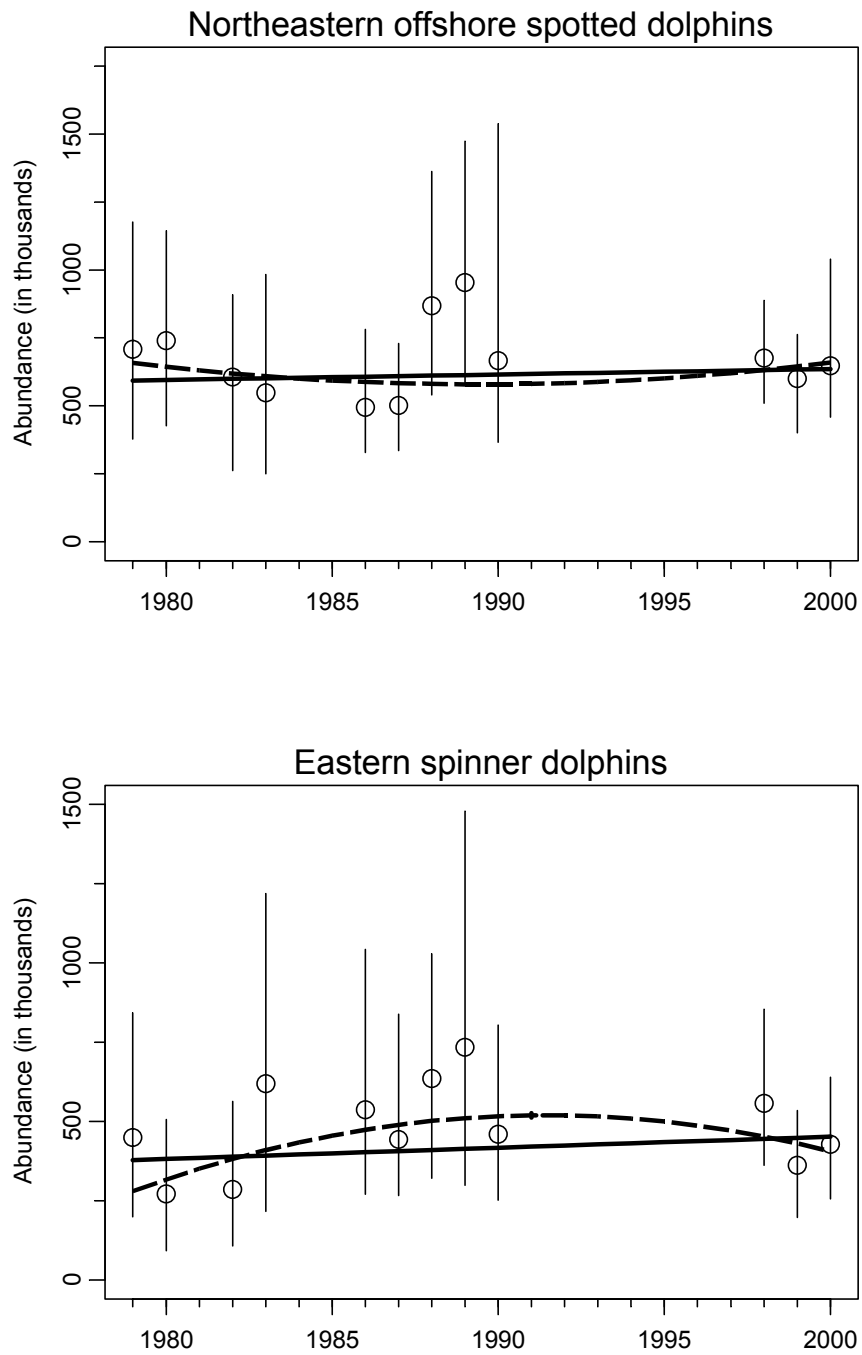


Fig. 9. Estimates of abundance for northeastern offshore spotted and eastern spinner dolphins, 1979-2000, with linear (solid line) and quadratic (dashed line) model fits.

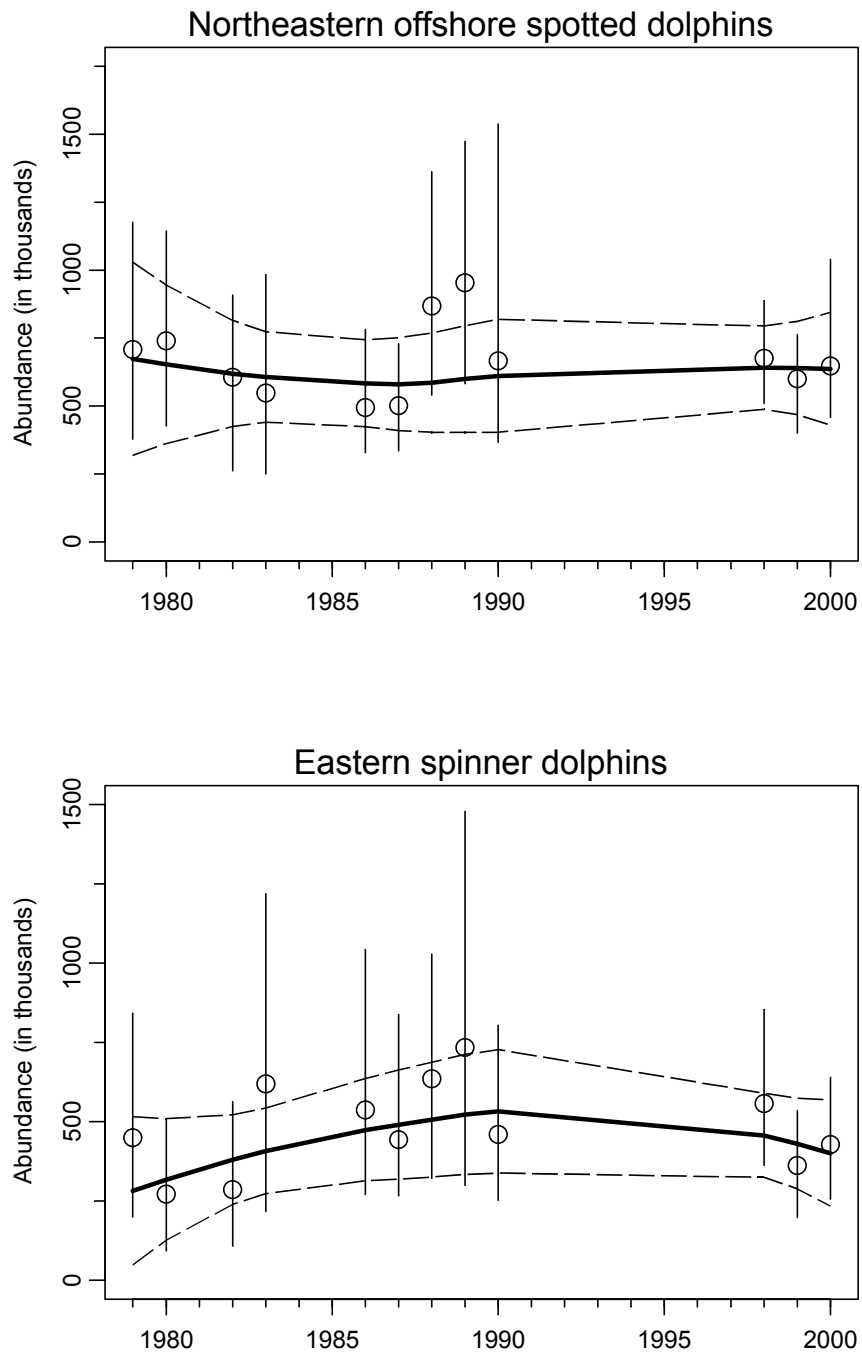


Fig.10. Estimates of abundance for northeastern offshore spotted and eastern spinner dolphins, 1979-2000, with weighted loess estimates (solid lines) and 95% confidence intervals on the smoothed estimates (dashed lines).

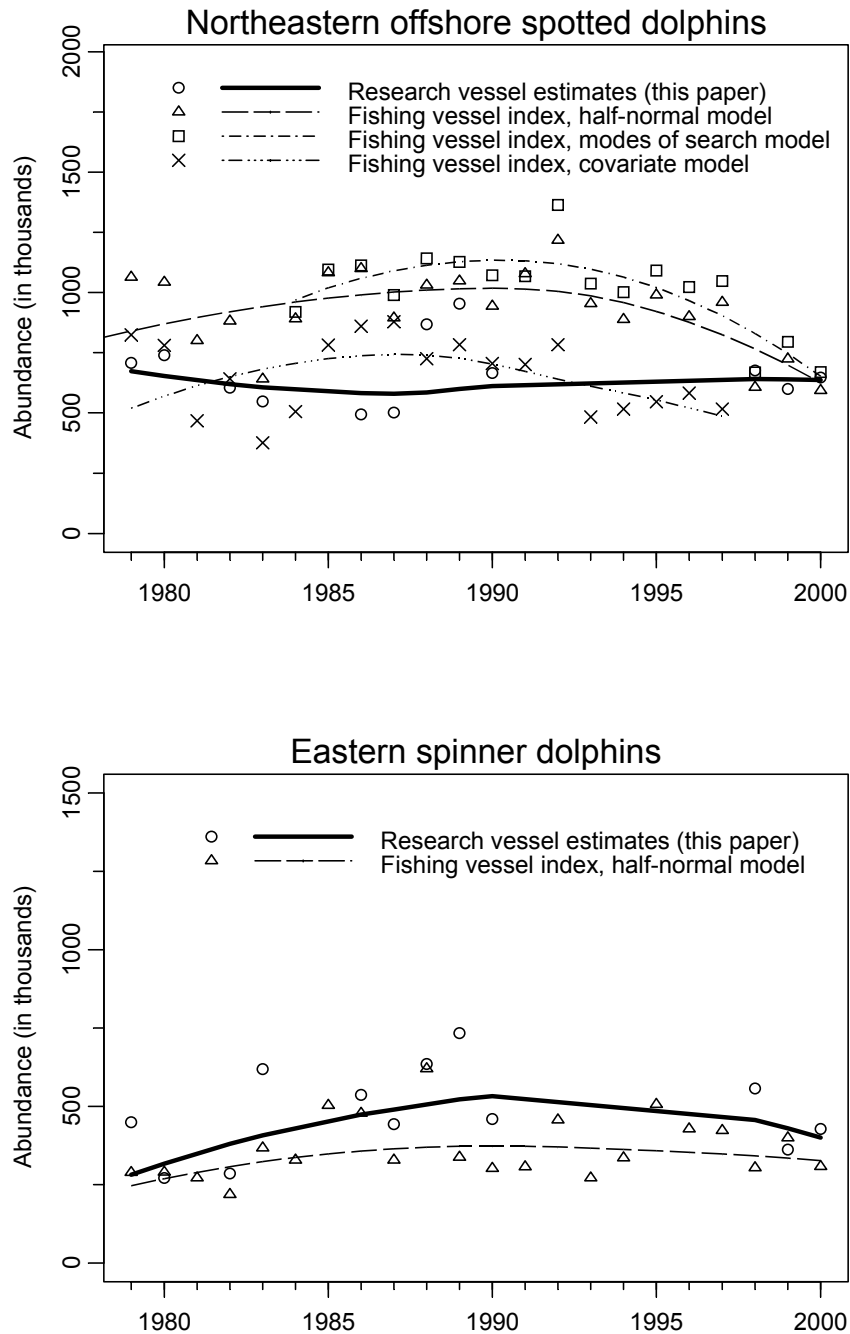


Fig. 11. Comparison of estimates of abundance for northeastern offshore spotted and eastern spinner dolphins, 1979-2000, based on data from research vessel surveys (this paper) with indices of abundance based on data collected by observers on fishing vessels. A weighted loess smoothed line is shown for each set of estimates. For the fishing vessel indices, the half-normal and modes-of-search model estimates are from Lennert-Cody et al. (2001), while the covariate model index is from Marques (2001).

## APPENDIX

Responses to comments provided by reviewers October 15-17, 2001. Page numbers refer to the reports submitted by each reviewer.

### Responses to comments by Dr. Bob Mohn

p. 4: Estimates of abundance were also carried out using Distance, ver. 3.5, which gave similar answers. Further simulation testing was carried out. Figs. 5 and 6 have been added to the paper to give a visual summary of fits to a half-normal function. The effects (compared to previous estimates) of various changes to the data and analysis have been assessed in the Discussion section.

p. 5: The sensitivity of the estimates to the new methods has been addressed in the Discussion section, including an assessment of the direction and magnitude of the changes. Most of the changes are small and provide more accurate measurements of fundamental quantities, such as school size and distance to sightings. We believe estimates are improved by using more accurate data, regardless of sensitivity. We confirm that the new data differ from the old in the expected direction by the expected amount. The most fundamental differences are due to the covariate modeling, which has been tested with simulations. See also the comments on testing of methods in Forcada (2002).

p. 5: Experience has shown that it is not efficient or feasible to assign fixed, pre-determined transects on a strictly random basis for ship surveys covering such large areas. The ships in this survey had strong constraints of time and area. Further, uniform random sampling was not required for population estimation. The ship tracklines were placed, prior to the cruise, without reference to cetacean density. During the cruise, many random factors affected the actual location where a transect was begun each day, such as weather and currents. This design ensured that the daily transects were sufficiently close to random. In fact, the main survey design worry during the cruise was to achieve adequate spatial coverage in the large area when bad weather prevented data collection for some area. The comments of Smith at a previous review suggested that adaptive sampling be considered. We have examined adaptive sampling, and rejected it in our situation for the following reasons: (1) the ETP surveys have to collect valid data on several species simultaneously; (2) the density of pelagic dolphins is so low that detecting a “patch” cannot be done on a time scale less than a day; and (3) it would be logistically difficult to keep the ship on schedule under adaptive sampling. Nevertheless, some modified line-transect techniques have recently been developed and we will consider them in the future.

p. 6: We agree that a consistent modeling approach across years would improve the estimates, and have implemented the half-normal model to achieve this. The half-normal model is modified in each year, and to a lesser degree for each species, by the particular sighting conditions encountered during each survey. Other comments on this page are more relevant to the assessment model than the actual population estimates.

## Responses to comments by Dr. Paul Medley

p. 5: Without doubt, the stability of the time-series of estimates could be improved by using some information, for example on detection probabilities, across years. However, for use in a population assessment model, it was important to maintain the independence of the estimate each year. We have implemented a single model of the detection function, namely the half-normal, which can be scaled by the sighting conditions specific to each year. The fact that some covariates, such as ship, are chosen in some years, but not others, can be understood by the correlation among the covariates. Many of the covariates are correlated, so that one covariate may act as a proxy for one or more others. In one year one of these is selected but another is selected in a different year. The ships cover different areas, for example, so that ship is a proxy for stratum, Beaufort, swell height, and other factors that differ among areas.

p. 6: Daily transects are not independent of each other. There are definitely oceanographic features on the scales on hundreds of kilometers that affect dolphin densities, and therefore contribute to a non-random pattern among daily transects. If definite boundaries could be identified, an improved bootstrap could be devised that would better reflect the spatial pattern. In our analysis, we have implemented a balanced bootstrap. Truncation of distant sightings is commonly used in distance analysis to improve the stability of the estimate of  $f(0)$  (Buckland et al, 2001).

p. 10: See comments above on choosing a consistent function to apply across all years. Also, in the revised analysis, multiple models are used each year, with weighting provided by AIC. This helps ensure that the effects of covariates in each year are accounted for, even if the covariates are not in the top (minimum AIC) model.

p. 12: The appendix contains a number of interesting thoughts on improving line-transect analysis. Some of them are related to radial distance models, which have been proposed in the past but shown to be less reliable than perpendicular distance models. In any case, these suggestions would require more research, development and testing before implementation.